TN-05
195454
508

NASA TN D-56

TECHNICAL NOTE
D-56

AN INVESTIGATION TO DETERMINE CONDITIONS UNDER WHICH DOWNWASH FROM VTOL AIRCRAFT WILL START SURFACE EROSION FROM VARIOUS TYPES OF TERRAIN

By Richard E. Kuhn

Langley Research Center
Langley Field, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON September 1959

(NASA-TN-D-56) AN INVESTIGATION TO DETERMINE CONDITIONS UNDER WHICH DOWNWASH FROM VTOL AIRCRAFT WILL START SURFACE EROSION FROM VARIOUS TYPES OF TERRAIN (NASA) 50 p

N89-70402

Unclas
00/05 0195454

ERRATA

NASA TN D-56

By Richard E. Kuhn

Page 27: A corrected figure 4(c) is attached for replacement of the original figure. The error corrected is in the small inset plots for which the scale increments in the abscissa x/D should be reduced by one-half.

Issued 12-22-59

NASA - Langley Field, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

TECHNICAL NOTE D-56

AN INVESTIGATION TO DETERMINE CONDITIONS UNDER WHICH DOWNWASH FROM VTOL AIRCRAFT WILL START SURFACE EROSION FROM VARIOUS TYPES OF TERRAIN

By Richard E. Kuhn

SUMMARY

Results of an investigation with small-scale equipment of the conditions under which the downwash from a hovering vertical-take-off-and-landing (VTOL) aircraft will start surface erosion indicate that the onset of erosion depends only on the dynamic pressure of the outward flow of air near the surface. For a rotor or propeller at a height of about 1 slipstream diameter above the surface, this surface dynamic pressure was found to be equal to the disk loading. For the VTOL aircraft supported by a ducted fan, the surface dynamic pressure with the ducted fan exit at a height of about 1 slipstream diameter is equal to one-half the exit-area loading. The surface dynamic pressure decreases rapidly with increasing height of the VTOL device.

Erosion of sand and loose dirt started at surface dynamic pressures of 1 to 3 lb/sq ft, which is in general agreement with helicopter experience. Thoroughly soaking the sand and loose-dirt surfaces increased the resistance to erosion to surface dynamic pressures of 30 to 50 lb/sq ft. Spray from water started at surface dynamic pressures of 1.5 to 2.5 lb/sq ft. Sod withstood dynamic pressures up to about 1,000 lb/sq ft.

INTRODUCTION

In the past few years a great variety of aircraft configurations have been proposed in which an attempt has been made to incorporate the vertical-take-off-and-landing ability of the helicopter with the high-speed potential of fixed-wing aircraft. These configurations range all the way from convertiplanes, which use helicopter-type rotors for hovering, to turbojet-supported types. A large amount of research work has been done to study the performance and stability and control characteristics of most of these configurations; however, little is known about the operational aspects of many of these types. The dust and debris that

the downwash from these aircraft may pick up has been particularly the subject of speculation, but little quantitative information is available.

Even the helicopter, with probably the lightest disk loading of any vertical-take-off-and-landing (VTOL) aircraft and therefore the lowest downwash velocity, raises considerable dust when operating over loose dirt or dry beach sand. (See, for instance, ref. 1.)[1] This dust cloud seldom seriously limits operations, but it is definitely a nuisance even for lightly loaded helicopters. Almost all the proposed VTOL types have higher disk loadings and, therefore, higher downwash velocities than the helicopter. It would be expected, then that the dust and debris problems associated with these types would be intensified.

The present investigation was undertaken in an attempt to provide some information on these problems. It was not expected that actual operational limits would be established from an investigation in which small-scale equipment was used, but rather the intent was to determine the manner in which the onset of disturbances varied with disk loading and height above various types of terrain. It is expected that the results obtained with the relatively wide range of downwash velocities and heights covered in this investigation will serve as a useful guide in interpreting and extrapolating results of later investigations and experience of full-scale configurations.

The primary assumption implied was that, so long as the particles involved were small with respect to the slipstream diameter, the onset of disturbances would be independent of the size of the downward-directed slipstream. The initial part of the investigation was conducted with the use of a 1-inch-diameter air nozzle to simulate the desired airstreams. Later, the investigation was expanded to use a 4-inch-diameter air nozzle and a 16-inch-diameter ducted fan in an attempt to check the primary assumption and also to obtain some information on recirculation effects.

SYMBOLS

The definitions of some of the symbols used are depicted in figure 1.

C_D drag coefficient of sphere, $\dfrac{\text{Drag}}{\frac{\rho}{2} V^2 \frac{\pi}{4}\left(\frac{d}{12}\right)^2}$

[1]Additional information on this subject was presented by Major W. J. Barrios, Army Aviation Board, Fort Rucker, Alabama, in a paper entitled "Some of the Operating Problems Encountered During Service Testing of the H-37A Helicopter" at the Fifth Annual Western Forum of the American Helicopter Society in Los Angeles, California, on September 26, 1958.

D	exit diameter of nozzle or ducted fan or effective diameter of slipstream from free propeller (0.707 propeller diameter), ft
D_p	diameter of free propeller, ft
d	particle diameter, in.
h	height of exit of nozzle or ducted fan above terrain surface, ft
h_s	height of survey station above terrain surface, ft
q	local dynamic pressure at any point in airstream, lb/sq ft
q_N	average dynamic pressure at exit of nozzle or ducted fan, lb/sq ft
R	Reynolds number, $\frac{d\rho V_t}{12\mu}$
T	total thrust of propeller or ducted fan, lb
V	airstream velocity, ft/sec
V_t	particle terminal velocity, ft/sec
W	weight or portion of aircraft weight supported by each propeller, lb
x	radial distance from center line of nozzle or ducted fan, ft
z	distance from exit of nozzle or ducted fan to survey station, ft
θ	inclination of axis of air jet, deg
μ	viscosity of air
ρ	mass density of air

Subscripts:

cr	critical
max	maximum

s surface

z at station z from exit

APPARATUS AND TESTS

One-Inch-Diameter Air Nozzle

The original intent of the investigation was to cover the entire range of downwash dynamic pressures likely to be encountered by the various VTOL configurations ranging from the helicopter to the turbojet-supported type. In order to simulate turbojet VTOL types with the available air supply, a 1-inch-diameter nozzle was employed. With this nozzle a dynamic pressure q_N range from 5 to 2,000 lb/sq ft could be obtained. This 1-inch nozzle was fitted to a plenum chamber, 6 inches in diameter and 6 inches in length, which was clamped to the platform of a manually operated hoist so that the entire assembly could be raised or lowered with respect to the surface under study (fig. 2). A simple scale (graduated in 1-inch increments) and a pointer were used to indicate height above the terrain. The nozzle dynamic pressure q_N of the airstream from the 1-inch-diameter nozzle was determined from the plenum-chamber pressure.

Four-Inch-Diameter Air Nozzle

A dynamic pressure range from 3 to 200 lb/sq ft was obtained with the 4-inch-diameter air nozzle. This nozzle was fitted to a plenum chamber, 12 inches in diameter and 12 inches in length, which was in turn mounted on a vertical-rail assembly (fig. 2). The nozzle and plenum chamber were raised and lowered at a fixed rate by means of an electric hoist. The height of the nozzle above the surface was indicated by means of a pointer and "ship's ladder" type of scale which consisted of crossbars at 16-inch intervals attached to flexible cables and suspended from the nozzle support. Thus, as the nozzle was lowered the scale folded up on the ground.

The nozzle dynamic pressure was measured by a single total-pressure probe at the center of the nozzle.

Sixteen-Inch-Diameter Ducted Fan

The possibility that the inflow to the supporting device on a VTOL aircraft might alter the dust and debris problem indicated the need for

tests with a device to simulate the appropriate inflow. A 16-inch-diameter ducted fan was used for this purpose. The ducted configuration was chosen instead of the free-propeller or rotor configuration simply because it was safer to operate. It was feared that repeated recirculation of particles through the propeller might cause a blade failure. For this reason, a duct consisting of a 1/4-inch-thick steel ring was placed around the propeller to contain the blades in case of failure.

A 56-horsepower model motor was used to drive a 6-blade fan. The blades were identical to those used in reference 2. A 1-inch-radius entrance lip was used.

The dynamic-pressure distribution at the exit of the fan was measured with a rake of total-pressure tubes and was integrated to obtain the average exit dynamic pressure q_N. This pressure was calibrated against the fan rotational speed for use in the dust and debris tests. The ducted fan assembly (fig. 2) was mounted on the same vertical rail and used the same scale as the 4-inch-diameter air nozzle.

Dynamic-Pressure Surveys

The surveys of the dynamic-pressure distribution in the slipstream at various distances downstream from the exit of the nozzle or ducted fan were made with a rake of 1/8-inch-diameter total-pressure tubes. The static pressure outside the region of ground effect was assumed to be atmospheric. Dynamic-pressure surveys of the outward flow along the surface were made with a rake of smaller diameter total-pressure tubes which were all parallel to the surface. Inasmuch as the primary purpose was to determine the dynamic pressures near the surface where the flow must be parallel to the surface, no attempt was made to correct for the angularity of the flow that exists because of the change in direction of flow from vertical to horizontal at some distance above the surface for positions close to the axis of the jet. Static pressures were measured on the surface at each survey station and were used with the total-pressure measurements to calculate the dynamic pressure near the surface.

Terrain Specimens

The types of terrain investigated were sand, loose dirt, water, and sod. The sand was ordinary builder's sand without special preparation other than adequate storage to insure dryness. The size distribution of the sand particles involved was determined by sifting the sand through wire screen of various wire size and mesh. The amount of sand that would pass through each size but would not pass through the next smaller size was weighed.

For the wet-sand test, the sand was thoroughly soaked and can be defined as being similar to that part of a beach that is repeatedly being washed by incoming waves.

The loose dirt consisted primarily of clay and was screened through a 1/4-inch-mesh sieve to exclude large pieces and rocks. The dirt was obtained from a location which was adequately protected from the direct effects of rain and weather. The dirt could not be described as being completely dry, however, since some moisture undoubtedly had been absorbed by osmatic action. The dirt-particle size distribution was determined in the same manner as the sand-particle size distribution.

The results for the size distribution of sand and dirt particles are as follows:

Particle size, d, in.	Percent by weight	
	Sand	Dirt
Larger than 0.051	8	30
0.019 to 0.051	32	16
0.015 to 0.019	14	7
0.010 to 0.015	13	20
0.0075 to 0.010	17	12
0.003 to 0.0075	15	7
Smaller than 0.003	1	8

For the tests with the 1-inch-diameter nozzle, the terrain specimens (except sod and water) were placed below the nozzle in a 30-inch-square box, and the terrain surface was carefully leveled before each test. The water was held in a tub about 20 inches in diameter and 10 inches deep and was carefully refilled before each test. For the sod tests, the apparatus was moved to a new section of undisturbed sod before each test.

It was feared that the test results with the 1-inch nozzle on water might have been affected by the reflection of the ripples or waves from the sides of the tub. A large pan, 6 feet square and 5 inches deep, was therefore constructed for use in the tests with the 4-inch nozzle and the 16-inch ducted fan. A 6-inch-wide "beach" with a slope of 2 inches per foot was added to this pan to help damp out the ripples and reduce the reflection effect.

The test procedure used for all tests was the establishment of the desired nozzle dynamic pressure with the nozzle at the highest distance attainable above the terrain specimen. Motion pictures were taken as the nozzle was lowered toward the surface.

Terminal-Velocity Measurements

An additional indication of particle size can be obtained from measurements of particle terminal velocity because at terminal velocity the effective drag is exactly equal to the particle weight. For very small diameters and low velocities (Reynolds numbers less than 1), the drag of a particle is proportional to the velocity rather than to the square of the velocity. Under these conditions, Stokes' equation for the terminal velocity of a sphere is

$$V_t = \frac{\text{Particle weight}}{3\pi\mu \frac{d}{12}}$$

where the particle diameter d is measured in inches. At higher velocities the drag is proportional to the square of the velocity, and the terminal velocity can be calculated from

$$V_t = \sqrt{\frac{\text{Particle weight}}{\frac{\rho}{2} C_D \frac{\pi}{4} \left(\frac{d}{12}\right)^2}}$$

These equations and the drag data of reference 3 have been used to calculate the terminal velocity of spheres of water and silicon (sand) shown in figure 3. Approximate measurements of the terminal velocity (which corresponds to the vertical updraft required to support the particle) of the largest and smallest particles involved were made by dropping the particles from a 16-foot height and timing the descent with a stop watch. The time required for the first particles to reach the ground was used in calculating the terminal velocity of the largest particles, and the time required for the last visible particles to settle to the ground indicated the terminal velocity of the smallest particles. Allowance for the time required to accelerate the particles to terminal velocity was made in calculating the results shown as follows:

Particles	Terminal velocity, V_t, ft/sec	Diameter of equivalent sphere, d, in. (from fig. 3)
Sand:		
Smallest particles . . .	2.5	0.005
Largest particles . . .	Over 30	0.06
Loose dirt:		
Smallest particles . . .	1.0	0.003
Largest particles . . .	About 30	0.06
Water	About 30	0.15

The measurements of terminal velocity of water drops were made by orally blowing water from a shallow pan. There is no assurance that the drops thus formed were the same size as those formed in the actual tests, but the results are given merely to indicate the approximate size and terminal velocity that were probable. The water and large particles of sand and dirt indicate a terminal velocity of about 30 ft/sec or greater. Accurate results in this range were difficult to obtain because of the short fall time involved and the reaction time of the person operating the stop watch.

PERTINENT FULL-SCALE PARAMETERS

In the present investigation, the downwash from a VTOL aircraft was simulated by either the exhaust from an air nozzle or from a ducted fan. In attempting to assess these results in terms of what might be expected with an actual aircraft, it is necessary to know at least the dynamic pressure in the downwash from the aircraft and the effective diameter of the airstream.

The average downwash dynamic pressure in the downwash from a hovering VTOL aircraft supported by a helicopter rotor or propeller can be computed from the momentum theory which indicates that half the velocity in the fully developed slipstream is attained at the rotor disk and that the area of the fully developed slipstream is half of the rotor-disk area. The thrust is given by

$$T = wV = \rho \frac{\frac{\pi}{4} D_p^2}{2} V^2$$

where w is the mass flow and V is the velocity in the fully developed slipstream. For hovering, $T = W$; therefore,

$$\frac{W}{\frac{\pi}{4} D_p^2} = \frac{\rho}{2} V^2 = q_N$$

Thus, the average dynamic pressure in the downwash from a helicopter rotor or VTOL propeller is equal to the disk loading at which it is hovering. Also, the diameter of the fully developed slipstream is 70.7 percent of the rotor or propeller diameter.

The duct or shroud around a ducted propeller prevents the contraction of the slipstream. The exit area of the duct (rather than the propeller disk area) is the controlling geometric parameter. Thus, the thrust is given by

$$T = \rho \frac{\pi}{4} D^2 V^2$$

and

$$\frac{W}{\frac{\pi}{4} D^2} = \rho V^2 = 2q_N$$

or

$$q_N = \frac{W/\frac{\pi}{4} D^2}{2}$$

Thus, the downwash dynamic pressure from a vehicle supported by a ducted fan is one-half of the exit-area loading, and the diameter of the slipstream is equal to the exit diameter. The turbojet types can be considered as an extension of the ducted fan concept with the added complications of temperature and compressibility effects.

RESULTS AND DISCUSSION

Some of the results of the present investigation are illustrated more graphically by motion pictures of the developing disturbances than is possible in a written presentation. For this reason a motion-picture film supplement to this paper has been prepared and is available on loan. A request card form and a description of the film will be found at the back of this paper immediately preceding the abstract and index pages.

Dynamic-Pressure-Distribution Surveys

As the airstream from a nozzle or propeller proceeded downstream, turbulent mixing with the ambient air caused a spreading of the jet and a reduction of the peak dynamic pressure at the center. Thus, it would be expected that the dust and debris problem created by any VTOL aircraft would be reduced as the height of the lifting device above the ground is increased. In order to determine this decay curve for each of the devices used in this investigation, surveys of the dynamic-pressure distribution in the slipstreams at various distances downstream (outside of the region of ground effect) were made and the results are shown plotted in figure 4.

Both the 1-inch and the 4-inch air nozzles produced very nearly rectangular velocity distributions within 1 diameter of the exit. This rectangular distribution deteriorated rapidly as the distance below the exit increased, and both nozzles exhibit essentially the same decay curve

at nozzle dynamic pressures below 200 lb/sq ft (fig. 4(a)). At higher nozzle dynamic pressures (fig. 4(b)), compressibility effects cause a somewhat more gradual decay with distance from the exit.

The dynamic-pressure distribution and decay curve for the ducted fan are compared in figure 4(c) with the distribution and decay curve for an 18-inch-diameter free propeller and with the decay curve for the air nozzles. Although the ducted fan exhibits a very distorted distribution at the exit (because of the large hub and large motor case which was too close to the duct inlet), the decay curves for the two rotor devices are very nearly the same at distances greater than 2 diameters from the exit (propeller disk for the free propeller) and are only a little above the decay curve for the air nozzles. Because the slipstream of a free propeller or rotor contracts rapidly behind the disk, the effective diameter of the slipstream was taken to be the momentum-theory value of the fully contracted slipstream. That is, outside the region of ground effect the effective diameter is 70.7 percent of the unshrouded propeller diameter. This conversion must be kept in mind when the results of the present investigation are evaluated with respect to other rotor or propeller data.

Surveys to determine the location of the maximum dynamic pressure of the air flowing parallel to the surface were made because motion pictures of the surface erosion indicated that the initial erosion started at some distance from the center of the airstream. This is not surprising inasmuch as it would be expected that a stagnation point would exist on the surface at the center of the airstream. The velocity very near the surface would be expected to increase rapidly from this point until a maximum is reached followed by a decrease with greater distances from the center. Vertical surveys of the dynamic-pressure distribution in the sheet of air flowing along the surface were taken at various radial distances from the center of the airstream and for various heights of the nozzle and ducted fan. Typical samples of the distributions obtained are shown in figure 5. This outward-flowing air sheet has a maximum thickness of about one-fourth of the airstream diameter and an approximately triangular dynamic-pressure distribution. The presence of the boundary layer at the surface alters this triangular distribution and causes the maximum to be reached at a slight distance above the surface (about 2 percent of the diameter for the present tests). The maximum dynamic pressure near the surface at any particular radial station will be referred to as the surface dynamic pressure q_s for convenience.

The variation of the surface dynamic pressure with radial station at various nozzle heights is presented in figure 6(a) for the 4-inch-diameter air nozzle. It should be noted that in the region in which the flow is changing direction from downward to outward, the maximum dynamic pressure may not be reached near the surface but at greater

heights if it is measured parallel to the local streamlines. Total-pressure tubes, which were parallel to the surface, do not give reliable data under conditions of high flow angularity; however, for the present purposes only the dynamic pressure near the surface is of interest, and here the flow must, of course, be essentially parallel to the surface.

With the nozzle close to the surface, the maximum surface dynamic pressure is reached at a distance of about 1 diameter from the center. At greater nozzle heights, the peak moves farther out probably because the airstream is spreading because of mixing and, therefore, acts like a larger airstream when it contacts the ground. Similar but less complete surveys were obtained for the 16-inch-diameter ducted fan (fig. 6(b)) and show essentially the same pattern. The flow-field surveys around a hovering rotor near the ground presented in reference 4 give some additional data along this line and are in general agreement with the results of the present investigation.

The decay curves of the maximum surface dynamic pressure (peak values from fig. 6) are plotted in figure 7 and are compared with the free-air decay curve for the air nozzles. It will be noted that the decay of surface dynamic pressure for the 4-inch air nozzle with nozzle height is more rapid than the free-air decay and also more rapid than that of the 16-inch ducted fan. This observation tends to indicate a scale effect which might be expected from considerations of the boundary layer. The boundary-layer thickness for an airstream of smaller diameter would be larger in respect to the overall thickness of the sheet of surface air and would cause a greater reduction in the surface dynamic pressure than would that for an airstream of larger diameter. Further investigations with larger-scale equipment will be needed to evaluate this effect.

Incipient Erosion

The investigation to determine the combinations of height and dynamic pressure at which erosion (dust or spray) began was made by establishing a dynamic pressure and then by steadily lowering the nozzle or ducted fan. The height at which surface erosion was first observable was determined from the motion pictures with the use of a time-study projector. The results are presented in figure 8 as the variation with dynamic pressure of the height at which erosion was first detected. The corresponding surface dynamic pressures at which erosion was first detected are presented as a function of nozzle dynamic pressure in figure 9. Heights of less than 1 diameter were avoided because at lower heights deviations from the established conditions occurred as a result of either back-pressure buildup in the nozzles or loss in thrust (and therefore loss in dynamic pressure) caused by proximity of the ducted fans to the ground.

Visual inspection of motion pictures of the tests to determine the conditions of incipient erosion yields a certain amount of scatter in the results because small amounts of erosion are not visible and because of individual differences in the interpretation of the pictures.

In general, the results indicate that the onset of erosion depends principally on the surface dynamic pressure and is relatively independent of the nozzle (or ducted fan) height or exit dynamic pressure which combine to produce the necessary surface dynamic pressure.

Sand.- Dry sand begins to move at surface dynamic pressures q_s somewhere in the range of from 1 to 3 lb/sq ft. This trend is in general agreement with experience with helicopters. Even lightly loaded helicopters with disk loadings of 2 to 3 lb/sq ft (dynamic pressure of 2 to 3 lb/sq ft) can raise considerable amount of dust when hovering low over a dry beach. Also, reference 5 indicates that in the study of sand storms, it has been found that a wind speed of 36 to 40 ft/sec will move sand. This speed corresponds to a dynamic pressure of about 1.5 to 2.0 lb/sq ft, which falls within the scatter band from the present investigation.

It should also be noted that the dynamic pressure at which erosion started was much higher than that corresponding to the free-fall or terminal velocity of the smaller particles involved. The dynamic pressure corresponding to the terminal velocity of the smallest sand particles was only about 0.01 lb/sq ft. If the terminal velocity of the smallest particles were the controlling parameter, dust would have been raised at nozzle heights of over 20 diameters even with the lowest disk loading investigated. On the other hand, the dynamic pressure corresponding to the terminal velocity of the largest particles is of the same order of magnitude as the surface dynamic pressures at which erosion started. Several factors probably influence the behavior and prevent the smaller particles from being picked up until higher dynamic pressures are reached. One of these factors is the presence of the boundary layer, which reduces the velocities to which these particles are subjected. Also, the smaller particles may be protected somewhat by the larger particles. Another factor is the attraction between particles and between particles and surfaces as discussed in reference 6, which indicates that the air velocity required to detach a small particle from a plate is much greater than the terminal velocity of the particle.

Careful study of the motion pictures indicates that the larger grains of sand began to roll first with almost all of the motion parallel to and very close to the surface. As the erosion proceeded, the removal of material from the immediate vicinity of the jet left a crater with upward sloping sides which increased the vertical projection of the particles.

Thoroughly soaking the sand with water greatly increased the resistance to erosion as is shown in figures 8(a) and 9(a). The results indicate that wet sand would withstand the downwash from a propeller or rotor with disk loadings as high as from 30 to 50 lb/sq ft. Apparently, the water increases the cohesion between particles. The erosion of wet sand started with chunks of sand breaking loose from the surface and being thrown outward rather than with individual grains of sand rolling outward as was observed with the dry sand. In the case of the 4-inch nozzle and 16-inch ducted fan, the sand was placed about 1/2-inch deep on a steel plate which was not perfectly flat. It was, therefore, difficult to obtain uniformly wet sand over the surface. In some places the excess water collected, and what appears in the motion pictures to be surface erosion is actually excess water being blown off. This is particularly true of the tests of wet sand with the 16-inch ducted fan.

One test in which the surface of the sand was only dampened to a depth of about 1/8 inch resulted in surface erosion almost as early as it occurred with dry sand. This fact clearly indicates that light sprinkling of water on sandy or dusty surfaces will not be sufficient. The exact depth to which the sand or dust must be soaked is not known; however, a simple calculation indicates that the weight of water needed for a soaking to only 1/8-inch depth would be of the order of one to two times the airplane weight.

Erosion of both the dry and wet sand started at some distance from the center of the airstream, and in the case of some erosions with the 1-inch air nozzle in which a pronounced hole was formed in the surface, a small peak was noticed at the center of this hole in the position of the stagnation point.

Comparison of the results obtained with the 4-inch nozzle with those obtained with the 16-inch ducted fan revealed no noticeable difference in the conditions at which erosion started that could be traced to recirculation. Some recirculation was observed, however, and is visible in the motion pictures of the tests with the 16-inch ducted fan. This recirculation probably consists almost entirely of the lighter, smaller particles which are merely carried along with the air moving into the fan. In order to protect the fan, the tests were always terminated when it appeared that the point was being reached at which noticeable quantities of dust were being drawn through the fan.

Dry loose dirt.- The results of the tests of dry loose dirt (figs. 8(b) and 9(b)) are in general very similar to those of the tests of dry sand, which is not surprising inasmuch as the particle sizes involved were about the same for sand and dirt. As with the dry sand, the erosion started with a few of the larger particles rolling radially outward.

The tests with the 1-inch air nozzle were made with the dirt contained in a box about 4 inches deep. Soaking the dirt with water resulted in only the top 1/2 inch being saturated with water. When extra water was added, it either ran off or slowly soaked through to the lower dry layer; thus, a balance was reached so that the top layers had a consistency that was fairly repeatable. The dry sublayer, however, caused spectacular eruptions as soon as erosion had removed the wet surface. In order to avoid the dry sublayer of the earlier tests, the loose dirt for the tests with the 4-inch nozzle and the 16-inch ducted fan was placed in a layer 1/2 inch deep on a steel plate. Unfortunately, this steel plate prevented the downward leakage of water with the result that the addition of an excessive amount of water resulted in mud. These differences in the consistency of the wet loose dirt are responsible for the wide scatter in the results shown in figures 8(b) and 9(b). Excess water was not a serious problem with the sand because, except for the water pockets mentioned previously, the water could drain through the sand and run off the edges of the plate. Unfortunately, the dirt continued to absorb water so that the consistency of the dirt went from dry to wet to mud and eventually could have reached the muddy-water stage. At some point in this progression, a maximum resistance to erosion would be found, but there is no assurance that the results obtained indicate this maximum.

Sod.- The results obtained with sod (fig. 8(b)) can be used only as a crude indication of the resistance to erosion because of the small size of the air jet employed and the coarse texture of the ground and vegetation. In the tests, the dry sod withstood nozzle dynamic pressures up to 2,000 lb/sq ft. In the tests of wet sod which were made the morning after a heavy rainfall, the sod withstood nozzle dynamic pressures up to 1,000 lb/sq ft. Thus, it would appear that any aircraft except a turbojet-supported type could easily operate from a terrain covered by unbroken vegetation. For prolonged operation, however, the vegetation may become dried out by the constantly repeated high-velocity airstreams, and the ground surface may become pulverized by repeated wheel passage. Even turbojet-supported aircraft may be able to make an emergency landing on good sod, but in this case the effects of exhaust temperatures of the order of 1,500° F must also be taken into consideration.

Water.- The criterion for incipient disturbance on water was taken as the point at which spray was first observed. Care had to be exercised in reading the film to differentiate between reflected light "highlights" on the film and true spray. The results presented in figures 8(c) and 9(c) indicate that spray will begin to appear at surface dynamic pressures of about 1.5 to 2.5 lb/sq ft. This trend is again in agreement with helicopter experience in which it has been found that a small amount of spray will be observed at disk loadings of 2 to 3 lb/sq ft.

The results obtained in the present investigation are also in good agreement with experience with the wind velocity at which spray has been observed on the open sea. Reference 7 indicates that spray is probable at wind velocities between 21 and 26 knots. These velocities correspond to dynamic pressures of 1.5 to 2.4 lb/sq ft, which are in excellent agreement with the present results.

Height Reached by Disturbance

Although the original purpose of the investigation was only to obtain information relative to the conditions at which a disturbance starts, it is also possible from the motion pictures to obtain some information concerning the maximum height at which dust or spray can be observed. The procedure was simply to judge visually the height reached by significant quantities of dust or spray for various combinations of nozzle height and nozzle dynamic pressure. These results in particular must be used with caution inasmuch as they depend upon the obscuration of visibility by airborne particles which can be greatly affected by the size of the device causing the disturbance.

The results obtained from tests with dry sand and loose dirt are presented in figure 10 as the height at which sand or dust was observed for various surface dynamic pressures. There is considerable scatter as would be expected but there appears to be no major difference between the results obtained with the 4-inch nozzle and those with the 16-inch ducted fan. It is interesting to note that the height reached by the sand appears to be proportional to the square root of the surface dynamic pressure and to lie somewhere between $1.5\sqrt{q_s}$ and $2.0\sqrt{q_{s,max}}$; that is, the height is proportional to the velocity. The heights at which dust from the loose dirt were observed are somewhat lower (fig. 10(b)). This may be because the loose dirt was not as dry as the sand.

Unpublished motion pictures of a full-scale turbojet hovering at an altitude of about 14 exhaust diameters over loose dirt showed the top of the denser part of the dust cloud at a height of about 27 diameters. Approximating the surface dynamic pressure from the curves of figure 7 with adjustments for compressibility effects from figure 4(a) would indicate a dust height of 24 diameters if the height is assumed equal to $2\sqrt{q_s}$. There were some wispy clouds of dust much higher than the top of the main cloud in the test of the full-scale configuration. These clouds would have been too faint to be seen in the test with the small-scale equipment of the present investigation. Considerably more data along this line will have to be obtained, particularly at large scales, before concrete reliance can be placed on the data in figure 10.

The height at which spray was observed (fig. 11) appears to be directly proportional to surface dynamic pressure. Probably the spray height is determined by the local slope of waves from which the spray is thrown and by random collisions of water droplets. Experience with spray from model hulls in towing-basin tests has indicated that the height to which spray is thrown is in correct proportion to the model size so long as the tests are run at the Froude number corresponding to the full-scale condition to be simulated. The Froude number is proportional to $\frac{V^2}{L}$ where L is a characteristics length or, in terms of the present investigation, Froude number would be proportional to $\frac{q_{s,max}}{D}$. Thus, tests of the 4-inch nozzle at a surface dynamic pressure of, for instance, $q_{s,max}$ = 1 lb/sq ft should correspond to tests of the 16-inch ducted fan at $q_{s,max}$ = 4 lb/sq ft. The spray height for the 4-inch nozzle should be one-fourth that of the 16-inch ducted fan when measured dimensionally, but the heights should be equal when nondimensionalized by division by diameter.

The results shown in figure 11 do not follow this analysis. The reason for this discrepancy is not known; however, examination of the motion pictures indicates that the water pan may have been too small for the tests with the 16-inch ducted fan. Unpublished motion pictures of a turbojet hovering over water also indicate that the data for the 4-inch nozzle may be more realistic than the data for the ducted fan. In the motion pictures of the turbojet hovering at an altitude of about 34 diameters, spray was observed at a height of about 18 diameters. The surface dynamic pressure was probably about 50 lb/sq ft, which places this experience with a full-scale configuration in better agreement with the data for the 4-inch nozzle than with the data for the 16-inch ducted fan.

There is, however, a distinct difference in the appearance of the spray produced by the turbojet and of that produced by the 4-inch air nozzle. The spray in the experience with full-scale configurations has a very fine textured, misty appearance; whereas, the spray from the 4-inch air nozzle has a very coarse and somewhat glassy appearance. Similar differences in appearance have been noted in tests of model hulls in towing-basin experiments. These differences in appearance are attributed to the effects of surface tension which prevent the breakup of the water into "scale sized" water droplets in the model tests. Towing tank experience has indicated, however, that the correctly scaled spray envelope is obtained from model tests at the proper Froude number although the appearance of the spray is entirely different.

Effect of Axis Inclination

The suggestion has been made that the effects of the high-energy downwash from VTOL aircraft of high disk loading might be reduced, so far as the immediate vicinity below the aircraft is concerned, by inclining the axis of the supporting airstream. This method, of course, requires two supporting airstreams inclined against each other to avoid horizontal acceleration, but for small inclinations the lift loss would be small.

This possibility was investigated by repeating some of the tests with inclinations of 15°, 30° and 45°. Although the influence of the other airstream was not simulated, the results shown in figure 12 indicate some reduction in the amount of spray or dust with increasing inclination. However, an inclination of about 45° would be necessary to blow all the products of the erosion away from the device. This would mean a lift loss of 30 percent of that which could be obtained with a vertical axis and, thus, makes the idea of inclining the axis appear impractical.

Related Phenomena and Other Investigations

The dust cloud raised by a hovering helicopter or VTOL aircraft in many respects resembles a dust storm or sand storm in miniature. A considerable body of literature about these storms exists and can be applied to the present problem. (See, for instance, refs. 5, 8, 9, and 10.) The mechanism by which sand is dislodged and carried aloft in a sand storm is described in reference 9 and is usually referred to as "saltation." Typically, a grain of sand or a small pebble begins to roll under the action of the wind and strikes other grains of sand. In some of these collisions, an occasional grain of sand receives an upward component of velocity. Once above the surface, this grain of sand picks up kinetic energy from the wind and, as a result, strikes the ground at a shallow angle and with much greater impact than was transmitted to it initially. The resultant impact usually projects additional grains of sand into the airstream, and thus a chain reaction is initiated which continues until the wind speed drops somewhat below the speed required to start the process.

In the atmosphere, there are always some turbulent eddies with random vertical as well as horizontal velocity components. The smaller particles are carried aloft by these vertical components and can be carried to extreme heights. The particles thus transported are quite small, however, because to be carried aloft their terminal velocity (fig. 3) must be lower than the random vertical velocities.

The process by which a dust cloud is started by a hovering helicopter or VTOL aircraft is apparently the same as that involved in dust storms. However, a major difference in the process of dust-cloud formation exists in that, with the hovering aircraft, the airstream along the ground which causes the erosion is relatively thin and has a maximum velocity very near the surface; whereas, in the natural sand storm, the airstream is approximately homogeneous and extends to great heights above the surface. In the case of the hovering aircraft, a secondary air current exists in addition to the primary flow of air from the rotor or other lifting device. This secondary flow consists of the movement of the ambient air that is caused by the entrainment of air by the primary outward flow along the surface. The turbulent eddies within this secondary flow carry the dust and sand particles aloft to form the dust cloud.

Evidence indicates that the vertical air currents existing in this secondary flow are much stronger than those in the atmosphere. For instance, the investigation of the amount of dust recirculated by a hovering helicopter reported in reference 1 found sand particles of 0.005- to 0.01-inch diameter with occasional particles as large as 0.08-inch diameter at altitudes of 20 feet above the surface. The secondary airflow then must contain vertical currents of at least 1 ft/sec or greater with some currents as high as 30 ft/sec. Although the sizes of sand in the dust cloud in the present investigation were not measured, the fact that the sand contained few particles less than 0.003 inch in diameter would indicate that the dust cloud must contain particles of at least 0.003-inch diameter.

The evidence concerning natural phenomena indicates vertical velocities much lower than 1 ft/sec. Reference 9, for instance, differentiates between dust storms and sand storms by defining dust as particles that are small enough to be carried to extreme heights and transported over great distances; whereas sand consists of particles that cannot be supported by atmospheric currents. Thus, central regions of large deserts, such as the Sahara, consist only of sand because all the dust has been carried off by the air currents. Since the sands in these regions contain few particles less than 0.003 inch in diameter, anything smaller than 0.003 inch in diameter can be supported by air. Reference 10 shows that since dust drifts in Kansas contain few particles less than 0.001 inch in diameter, smaller particles are carried off with the wind. In the investigation reported in reference 11 the sizes of dust particles carried by the air at White Sands, New Mexico, were measured and it was found that 99 percent of the dust consisted of particles less than 0.001 inch in diameter with only occasional particles as large as 0.004 inch in diameter. Thus, the natural vertical currents must consist generally of velocities of the order of 0.001 to 0.01 ft/sec, with velocities as high as 1 ft/sec possible occasionally.

SUGGESTIONS FOR FUTURE RESEARCH

The foregoing discussion indicates that a study of the secondary flow of air in the region directly above the primary outward-flowing sheet of air on the surface could be of considerable help in understanding the mechanism by which dust clouds are formed. Such a study should include a determination of both the horizontal and vertical components of velocity and the way in which these components vary with time for a considerable number of points in the region of the rotor.

The present investigation was conducted by lowering the nozzle or ducted fan to the surface at a constant rate. It is probable that the dust cloud would be larger and denser if the VTOL device was held at a fixed height above the surface for a finite length of time. Further investigation appears to be needed on this point.

Further studies of scale effects, particularly tests with equipment approximating full-scale devices, are needed to define the limits of applicability of the data obtained in the present investigation.

The present investigation touched on the problems of the jet VTOL aircraft only briefly. The effects of exhaust temperatures of the order of 1,500° F were, of course, completely ignored in the present study but could be of major significance in practical application with full-scale configurations. Surveys of both the dynamic-pressure and temperature profiles near the surface at various distances from the axis of the jet would be of value in assessing the dust and debris problem and evaluating suggested means of treating operational sights. The surveys would also be helpful in analyzing results of tests of full-scale turbojets over various surfaces.

The present investigation involved only flat surfaces. The presence of obstructions such as large rocks, other aircraft, ground equipment, or uneven ground would be expected to affect seriously and adversely the entire problem of erosion. Also, the presence of two or more slipstreams operating in close proximity, such as those with multipropellered VTOL aircraft, would be expected to aggravate the problem of upward projection of dust and debris in the mixing region where the outflow from the slipstreams meet.

The beneficial effect of soaking the surface in increasing the resistance of sand and dust to erosion suggests that some of the soil-stabilization techniques (ref. 12) may be of considerable help in this problem. Simply oiling the surface may be sufficient for some applications. Additional work over various types of treated terrain is needed. Also, the foregoing analysis of the primary and secondary flows involved suggest that some form of portable perforated plates supported a short

distance above the ground might be effective in two ways. First, the plates would reduce the dynamic pressure of the air passing through them; thus the erosion tendency would be reduced. Second, a substantial outward flow on the surface of the plates might catch and carry radially outward a sufficient amount of the dust particles that are raised so that operations would be possible.

CONCLUDING REMARKS

The results of the present investigation using small-scale equipment can give only an indication of the conditions under which surface erosion first starts. Helicopter experience indicates that satisfactory operations can be carried on even in the presence of surface erosion and a developing dust cloud. Therefore, the present investigation should not be used to attempt to set operational limits.

Inasmuch as sod withstands erosion up to downwash dynamic pressures (disk loadings) of almost 1,000 lb/sq ft, it would appear that at least a limited operation from firm ground covered with unbroken vegetation should be perfectly satisfactory for almost all vertical-take-off-and-landing (VTOL) types except turbojet-supported aircraft. Prolonged operation, however, may dry out the vegetation, and traffic may pulverize the soil to the point that dust and dried and broken vegetation would become a problem.

In general, the results indicate that the onset of erosion depends primarily on the dynamic pressure of the outward flow of air parallel to the surface and is relatively independent of the nozzle or ducted-fan height or exit dynamic pressure which combine to produce the necessary surface dynamic pressure.

The results of the present investigation with respect to loose dry dirt and dry sand agreed with helicopter experience in indicating surface erosion at very low downwash dynamic pressures. Thoroughly soaking the surface with water delayed the onset of erosion to surface dynamic pressures that would be obtained with aircraft supported by propellers or rotors with disk loadings of 30 to 50 lb/sq ft. This experience with wetting the surface suggests that some of the soil-stabilization techniques currently available may be able to provide adequate operating surfaces.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., April 13, 1959.

REFERENCES

1. Watjen, E. A.: Amount of Dust Re-Circulated by a Hovering Helicopter. Rep. No. R-169 (Contract No. NOa(s)53-1102c), The Kaman Aircraft Corp., Dec. 1956.

2. Taylor, Robert T.: Experimental Investigation of the Effects of Some Shroud Design Variables on the Static Thrust Characteristics of a Small-Scale Shrouded Propeller Submerged in a Wing. NACA TN 4126, 1958.

3. Hoerner, Sighard F.: Aerodynamic Drag. Publ. by the author (148 Busteed, Midland Park, N. J.), 1951.

4. Fradenburgh, Evan A.: Flow Field Measurements for a Hovering Rotor Near the Ground. Sikorsky Aircraft Div., United Aircraft Corp., 1958. (Presented at Am. Helicopter Soc. Fifth Annual Western Forum (Los Angeles, Calif.), Sept. 25-26, 1958.)

5. Combier, Ch.: Étude des mouvements de l'air dans les vents de sable. Mémorial de la Météorologie Nationale, No. 35, 1951.

6. Jordan, D. W.: The Adhesion of Dust Particles. The Physics of Particle Size Analysis. British Jour. of Appl. Phys. (Supp. No. 3), 1954, pp. S 194 - S 197.

7. Russell, R. C. H., and MacMillan, D. H.: Waves and Tides. Hutchinson's Scientific and Technical Publications, 1952.

8. Bagnold, Ralph A.: The Physics of Blown Sand and Desert Dunes. William Morrow and Co. (New York), 1942.

9. Zingg, A. W., and Chepil, W. S.: Aerodynamics of Wind Erosion. Agricultural Engineering, vol. 31, no. 6, June 1950, pp. 279-282, 284.

10. Layton, Ivan: Atmospheric Particle Size Distribution. Tech. Memo. 482, Missile Geophys. Div., U. S. Army White Sands Signal Agency, Dec. 1957.

11. Pickett, Andrew G., and Lemcoe, M. M.: Research Studies of Methods for Increasing Soil Trafficability. Rep. No. TR58-210 (Contract No. AF-19(604)2217), Southwest Res. Inst., Dec. 1957.

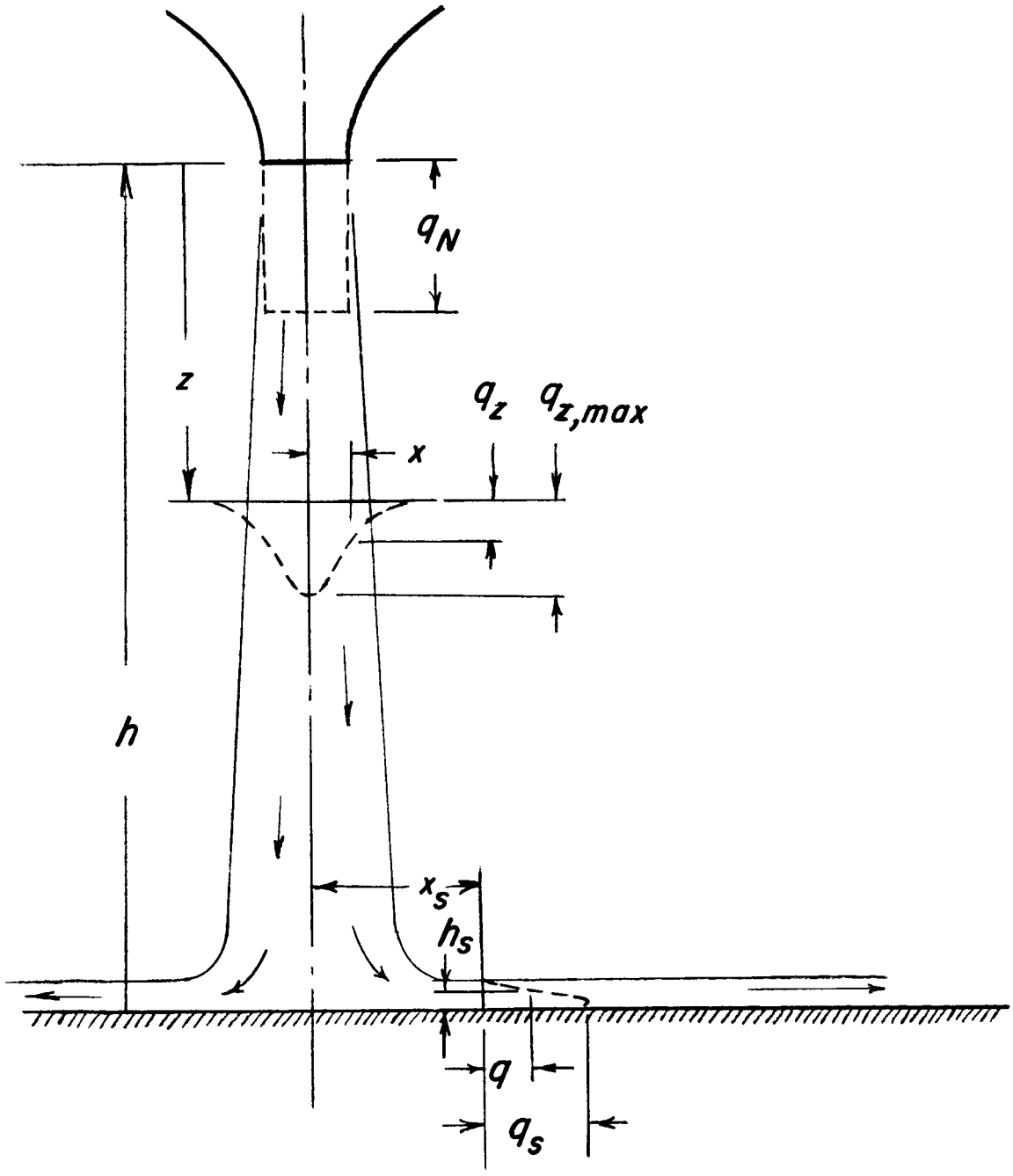
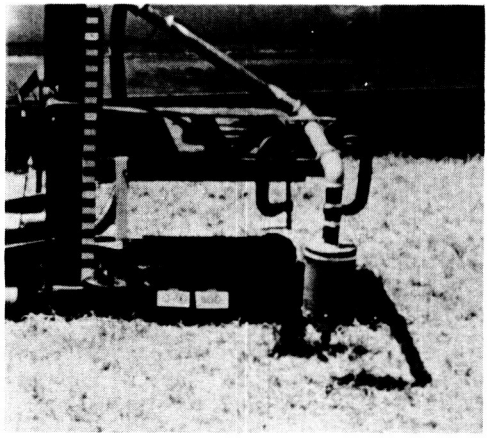
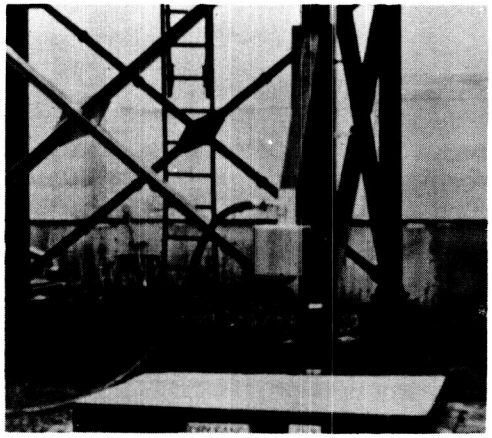


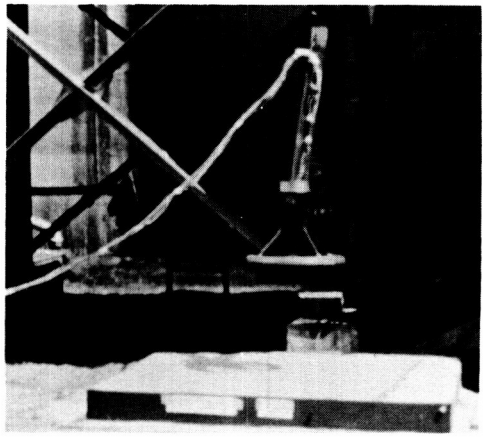
Figure 1.- Schematic diagram of airflow defining some of the symbols used.



1-inch-diameter air nozzle



4-inch-diameter air nozzle



16-inch-diameter ducted fan

L-59-1944

Figure 2.- Photographs of equipment used in investigation.

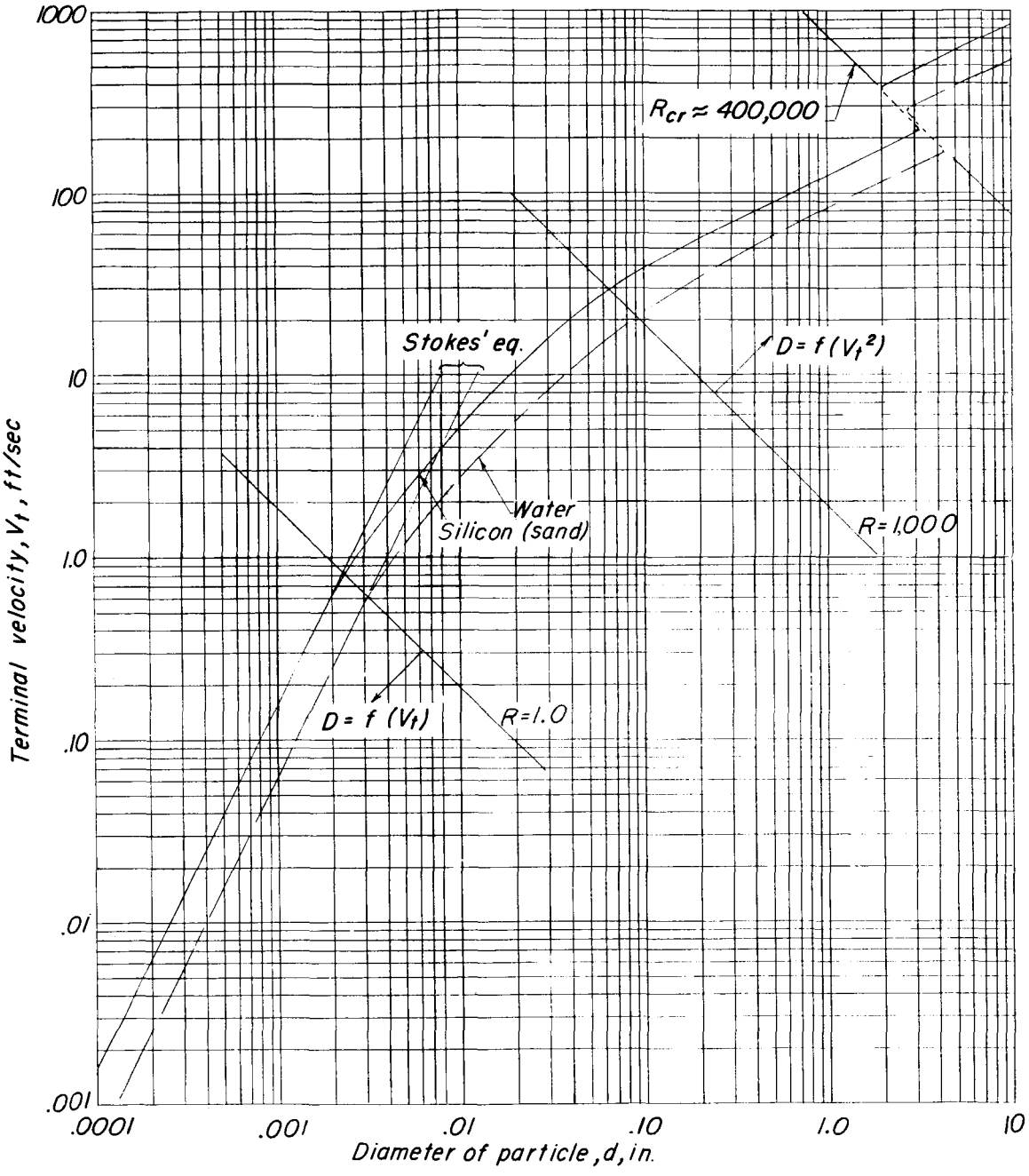
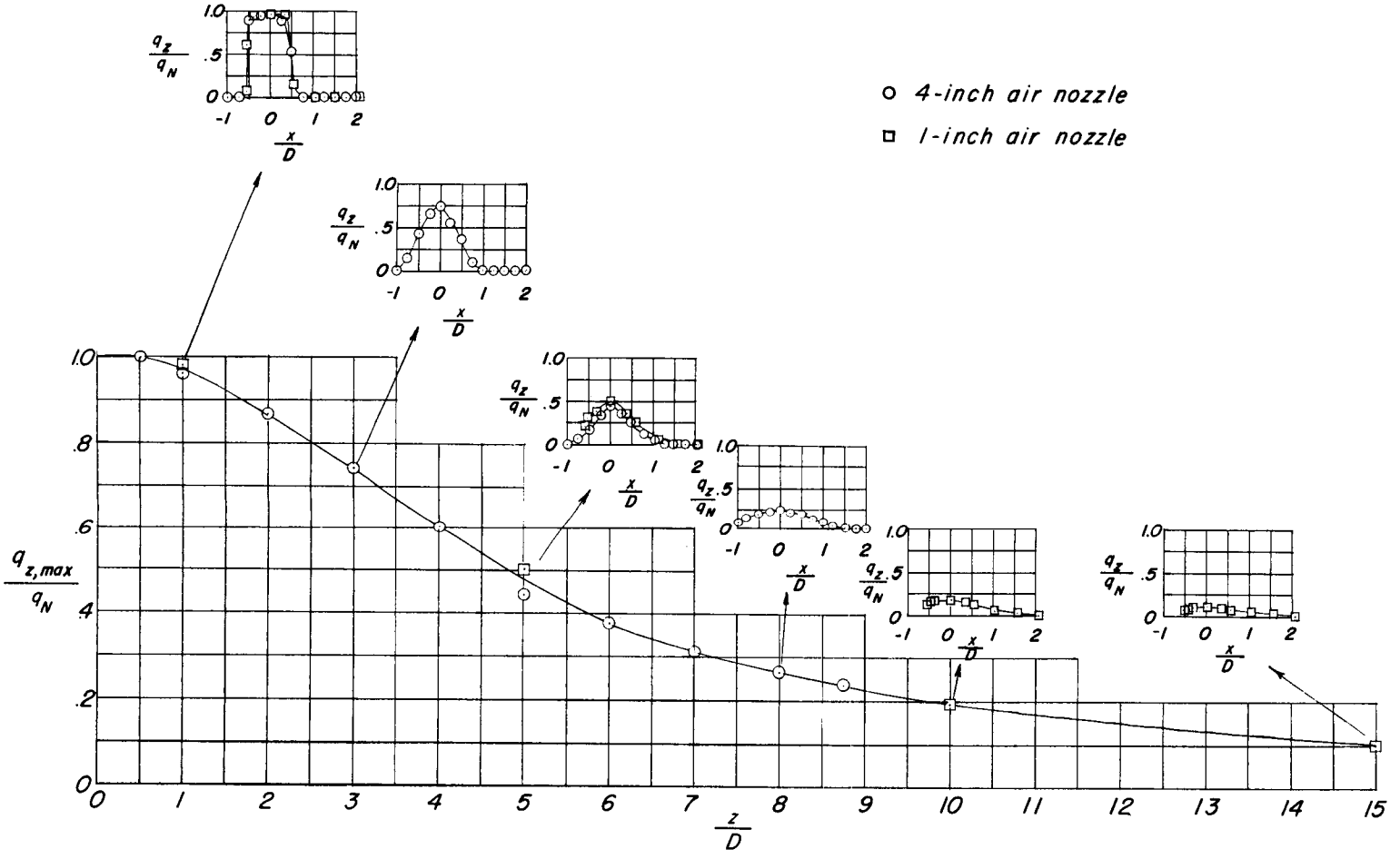
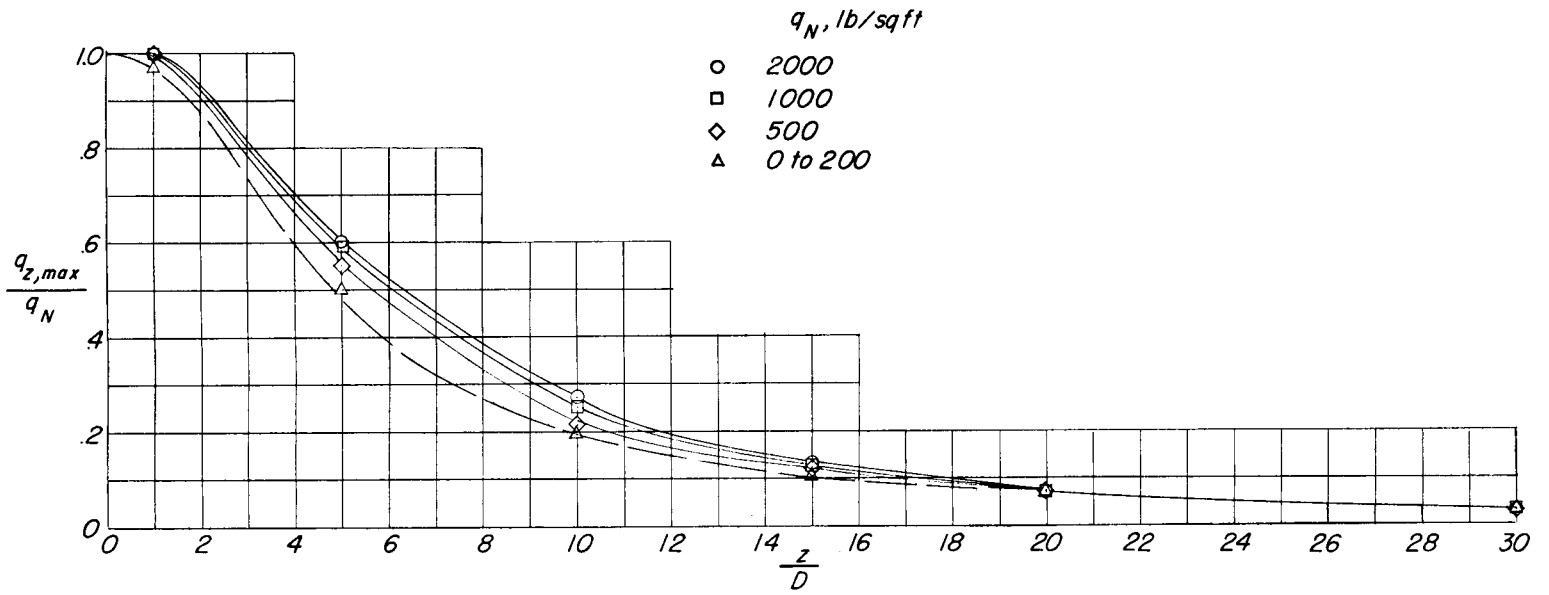


Figure 3.- Variation of terminal velocity of particles with particle diameter.



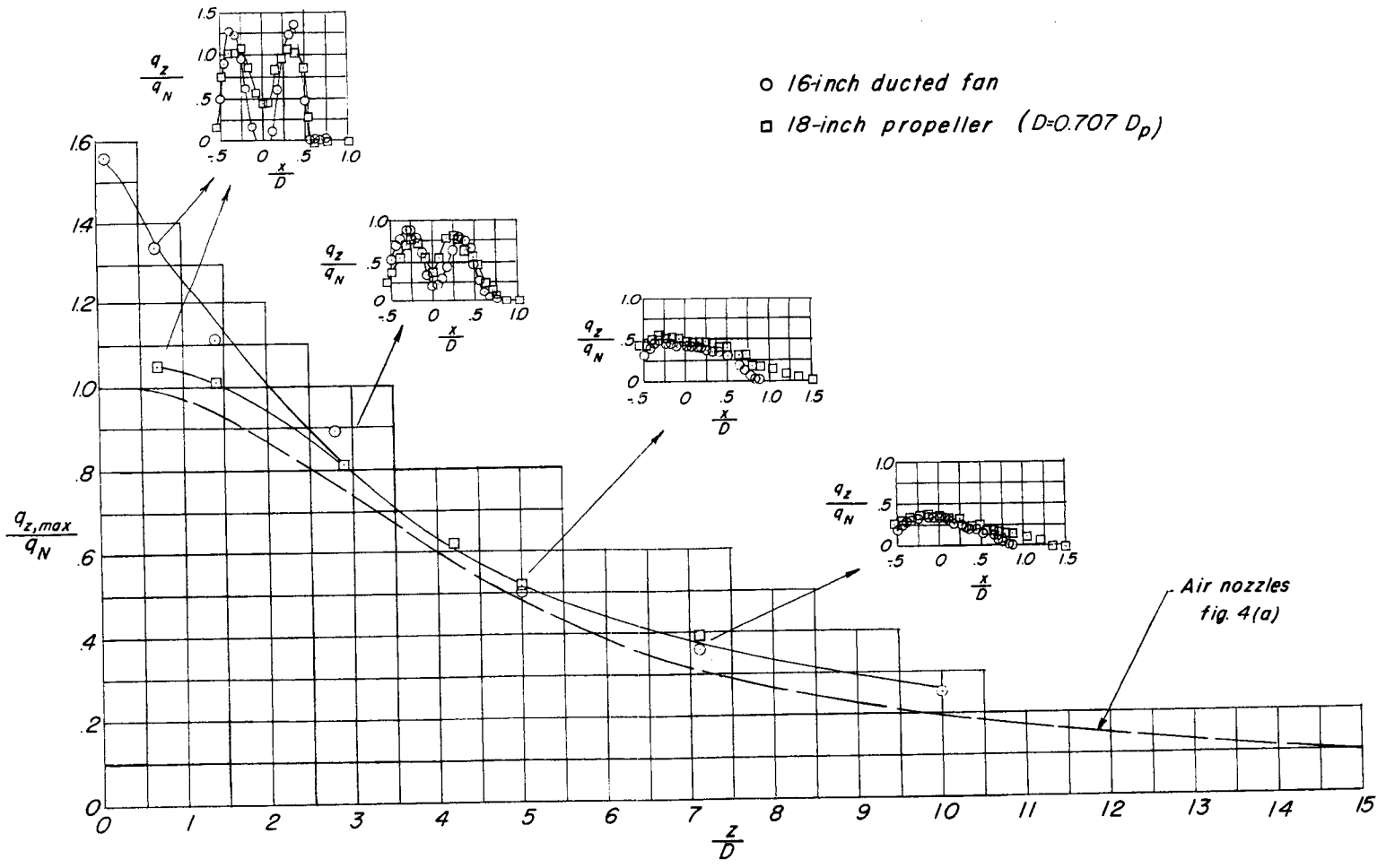
(a) Air nozzles; $q_N < 200$ lb/sq ft.

Figure 4.- Decay of dynamic pressure with distance from exit in free air.



(b) 1-inch air nozzle.

Figure 4.- Continued.



(c) 16-inch ducted fan and 18-inch free propeller.

Figure 4.- Concluded.

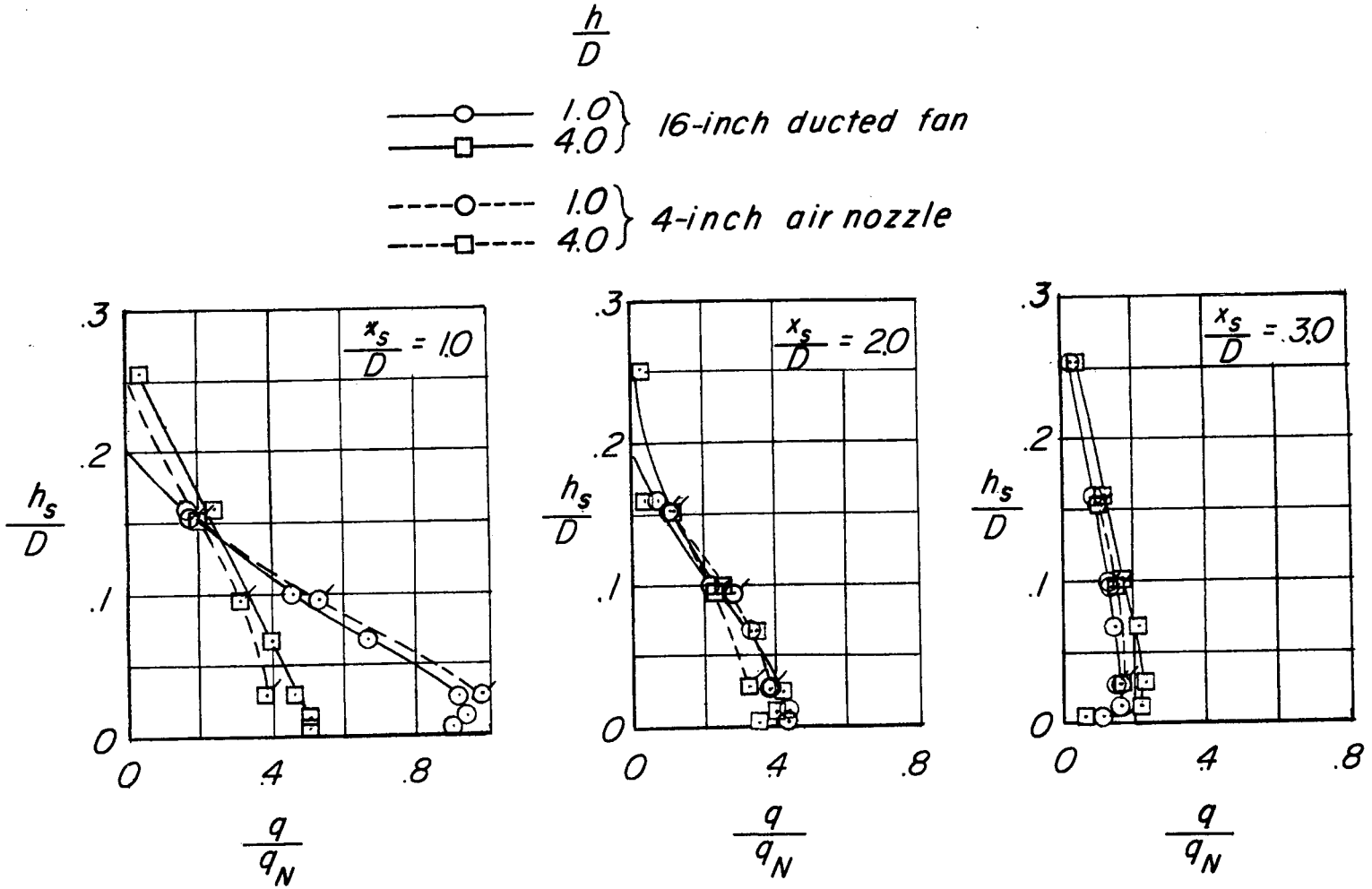
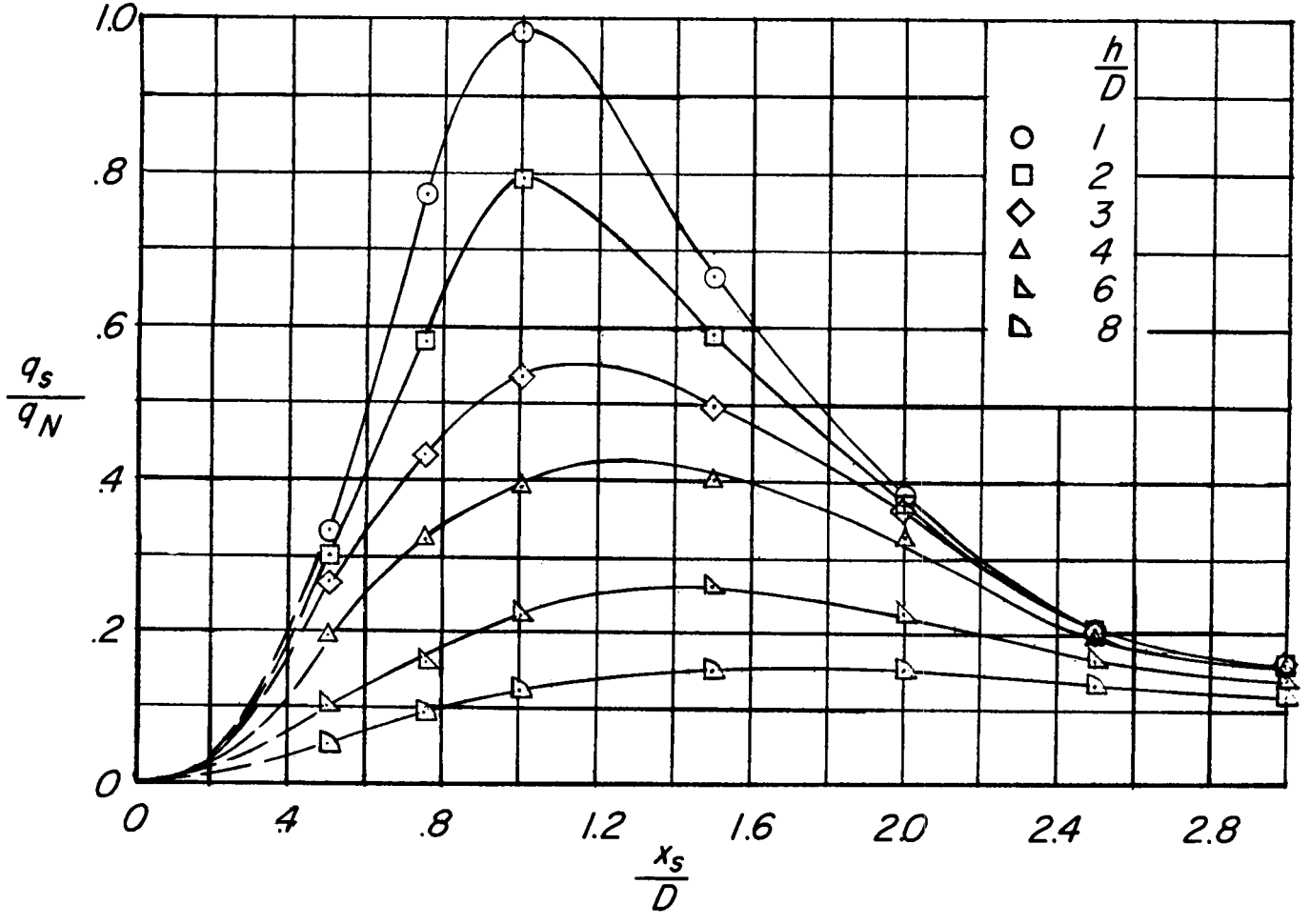
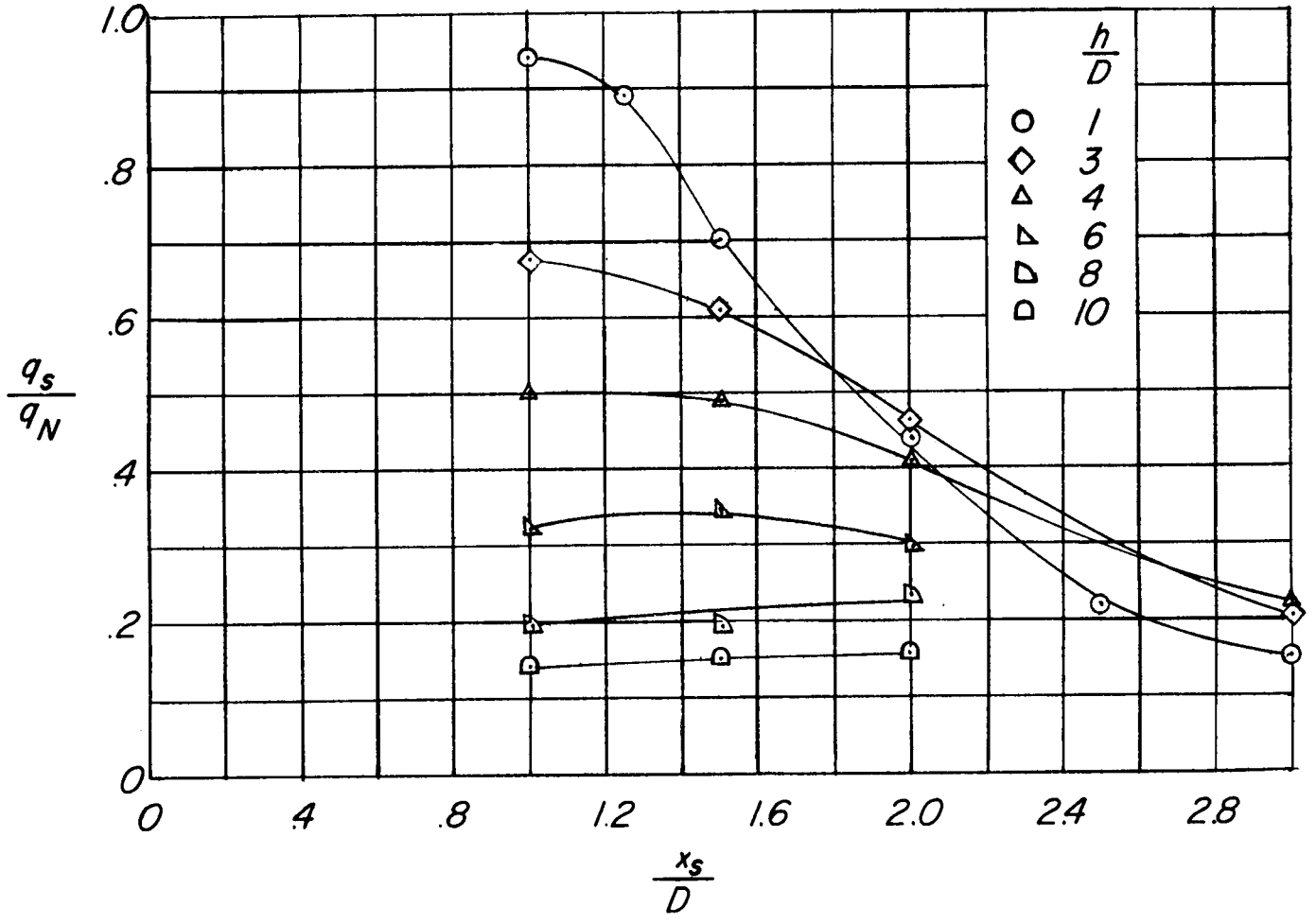


Figure 5.- Typical dynamic pressure profiles of outward flow of air along terrain surface.



(a) 4-inch air nozzle.

Figure 6.- Variation of peak dynamic pressure near the surface with radial distance from center line for various heights of exit above surface.



(b) 16-inch ducted fan.

Figure 6.- Concluded.

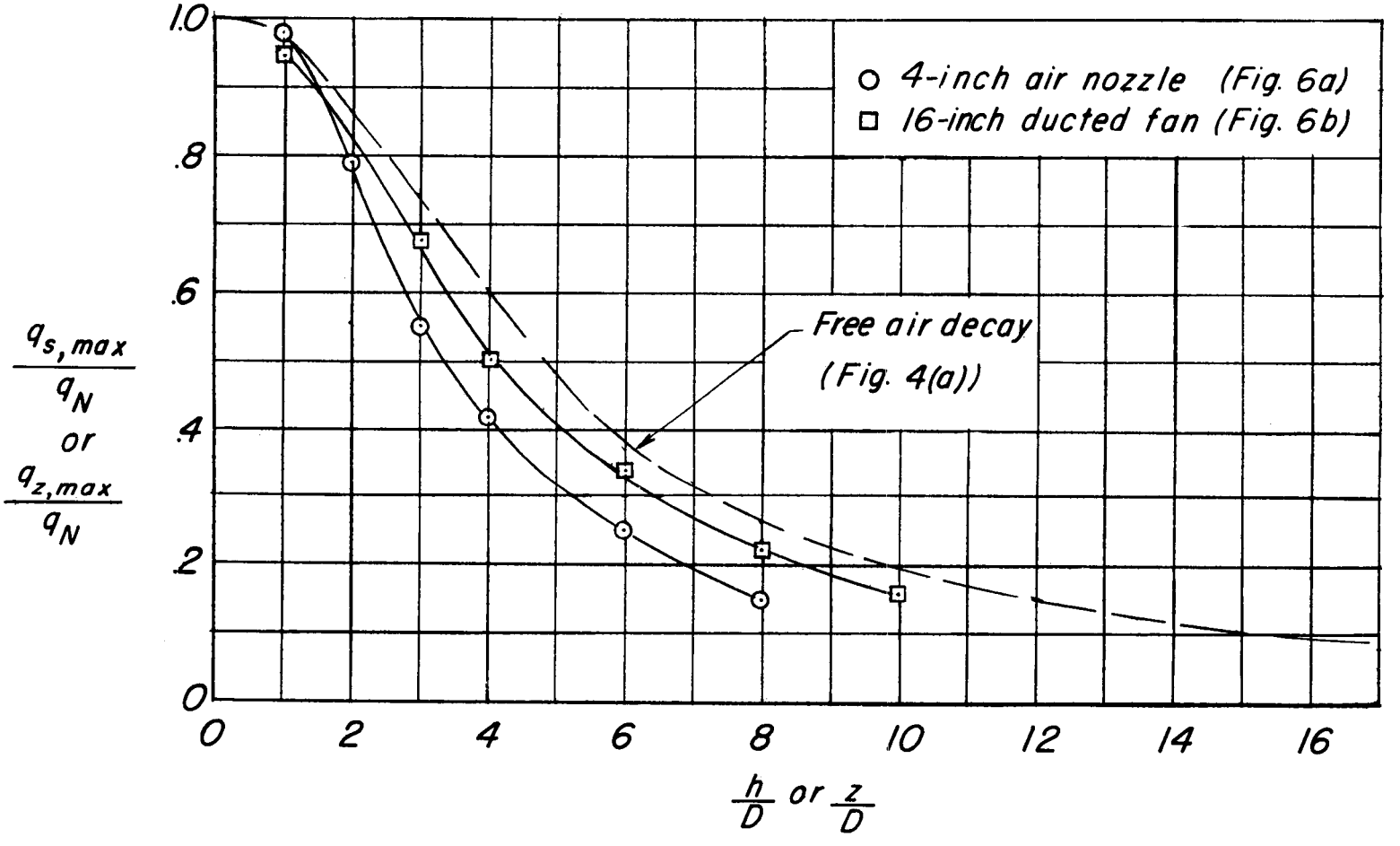
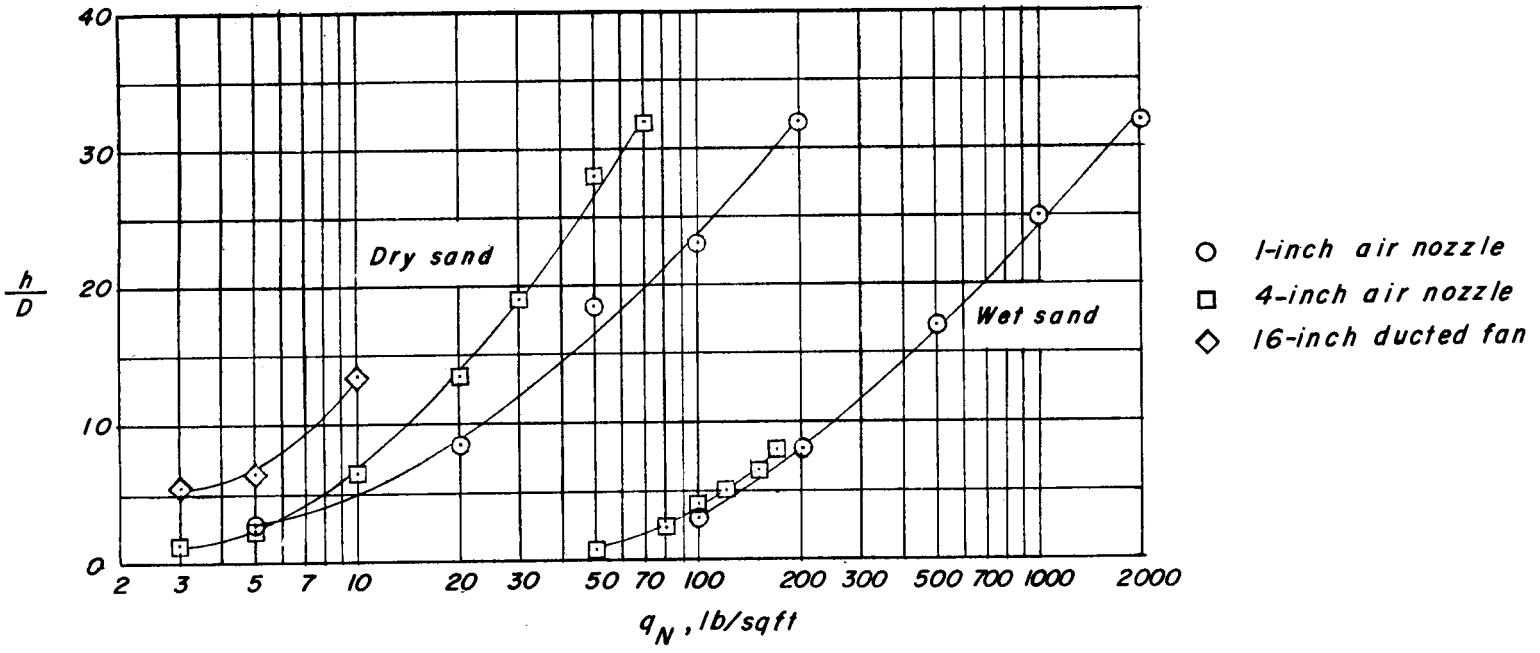
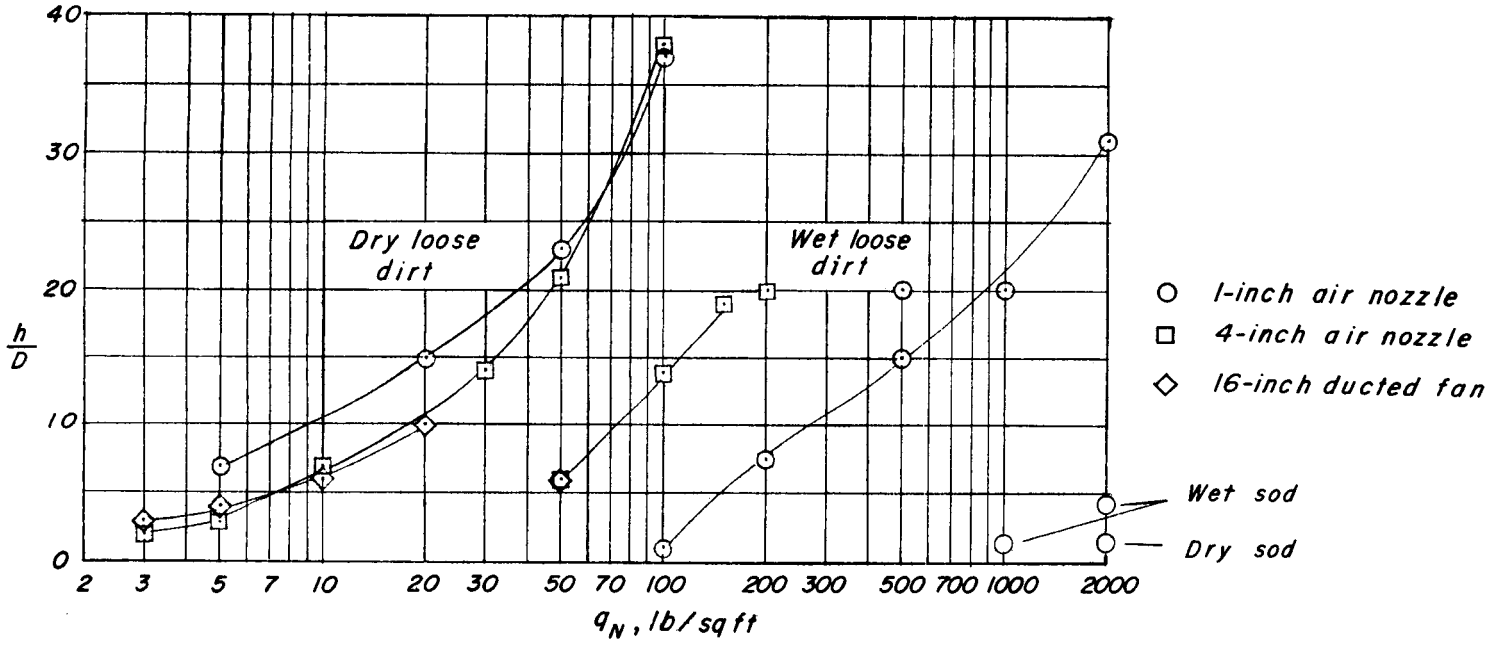


Figure 7.- Maximum dynamic pressure near surface.



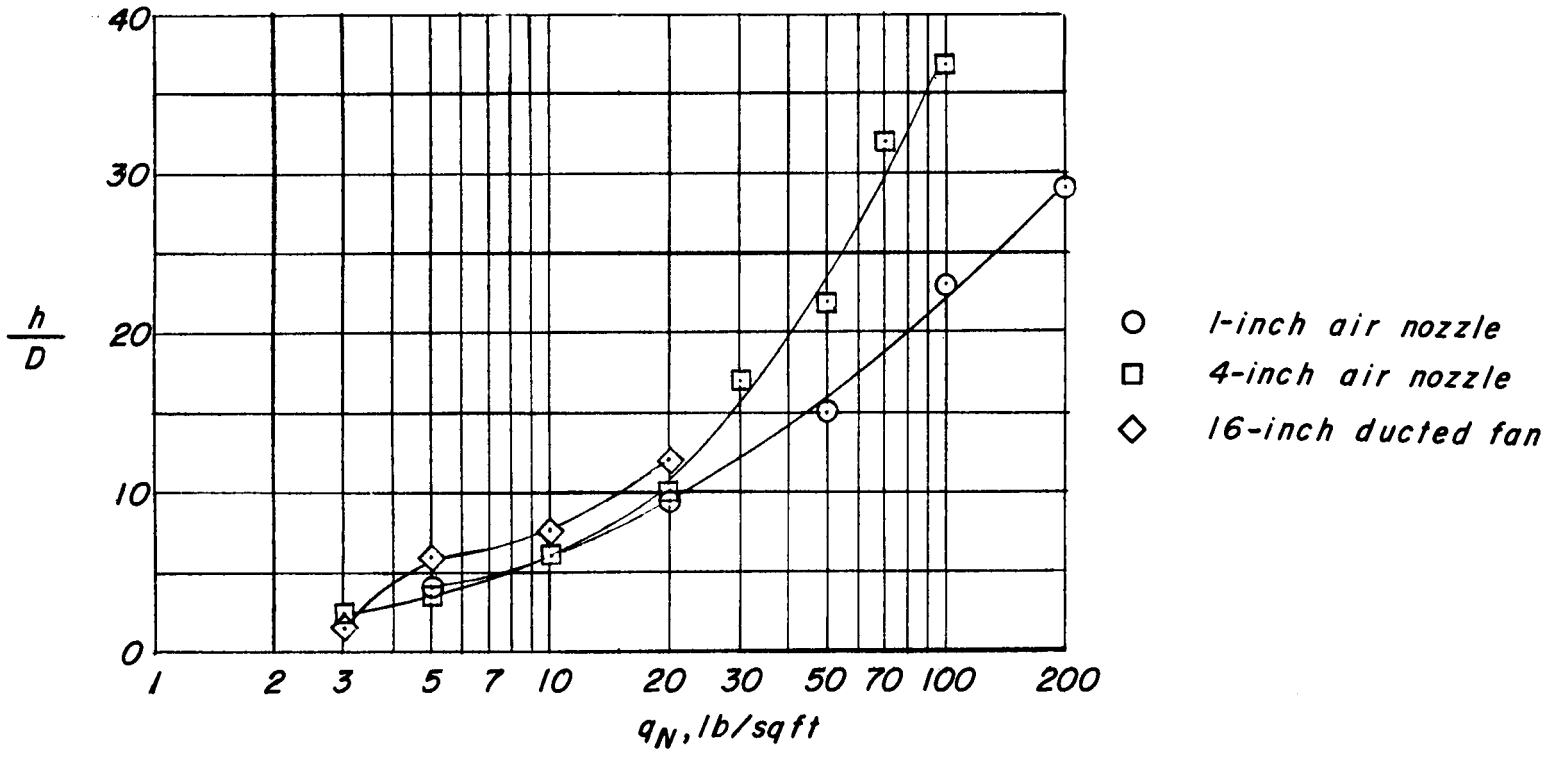
(a) Sand.

Figure 8.- Variation of height at which disturbance was first detected with nozzle dynamic pressure.



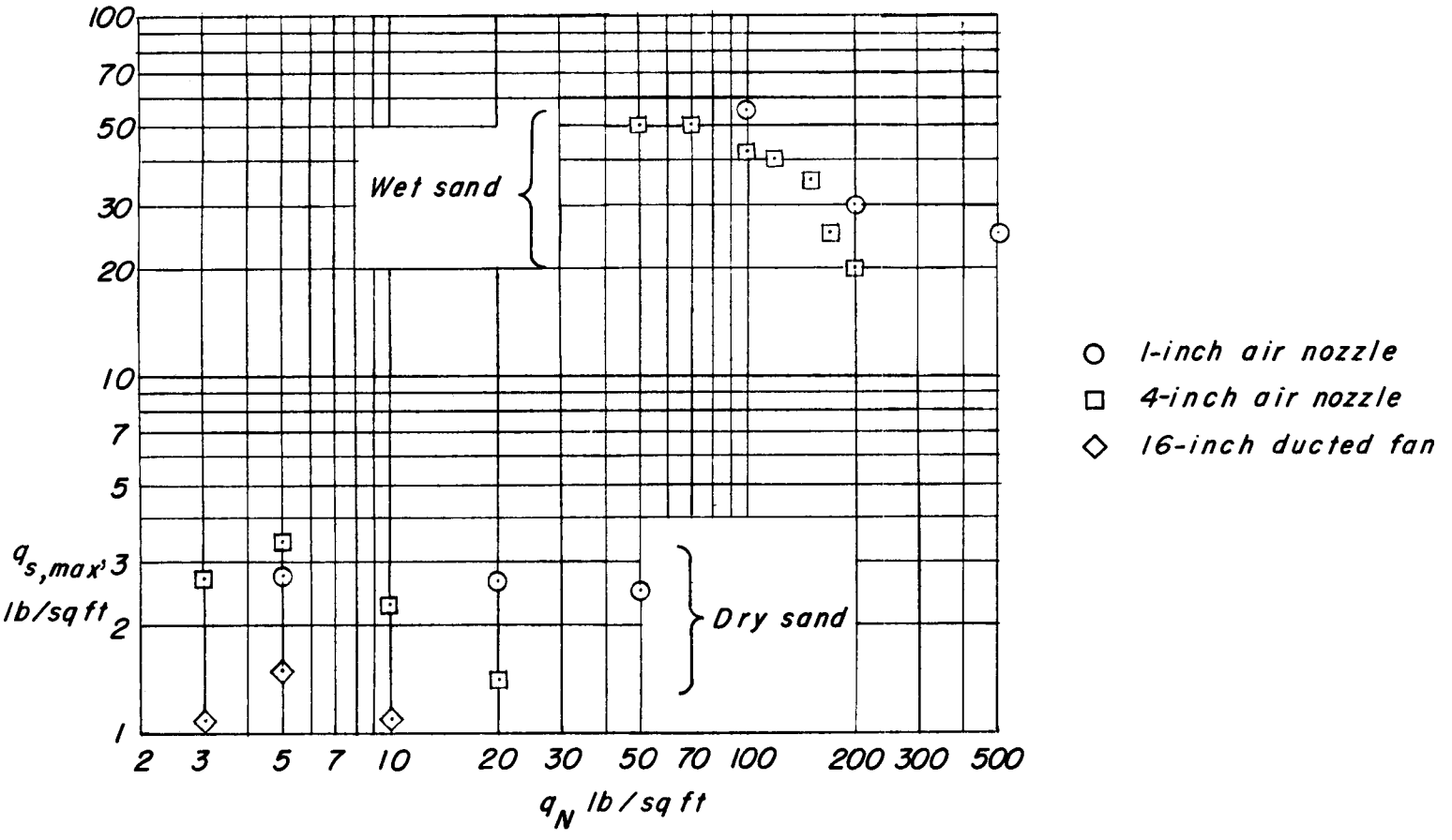
(b) Loose dirt and sod.

Figure 8.- Continued.



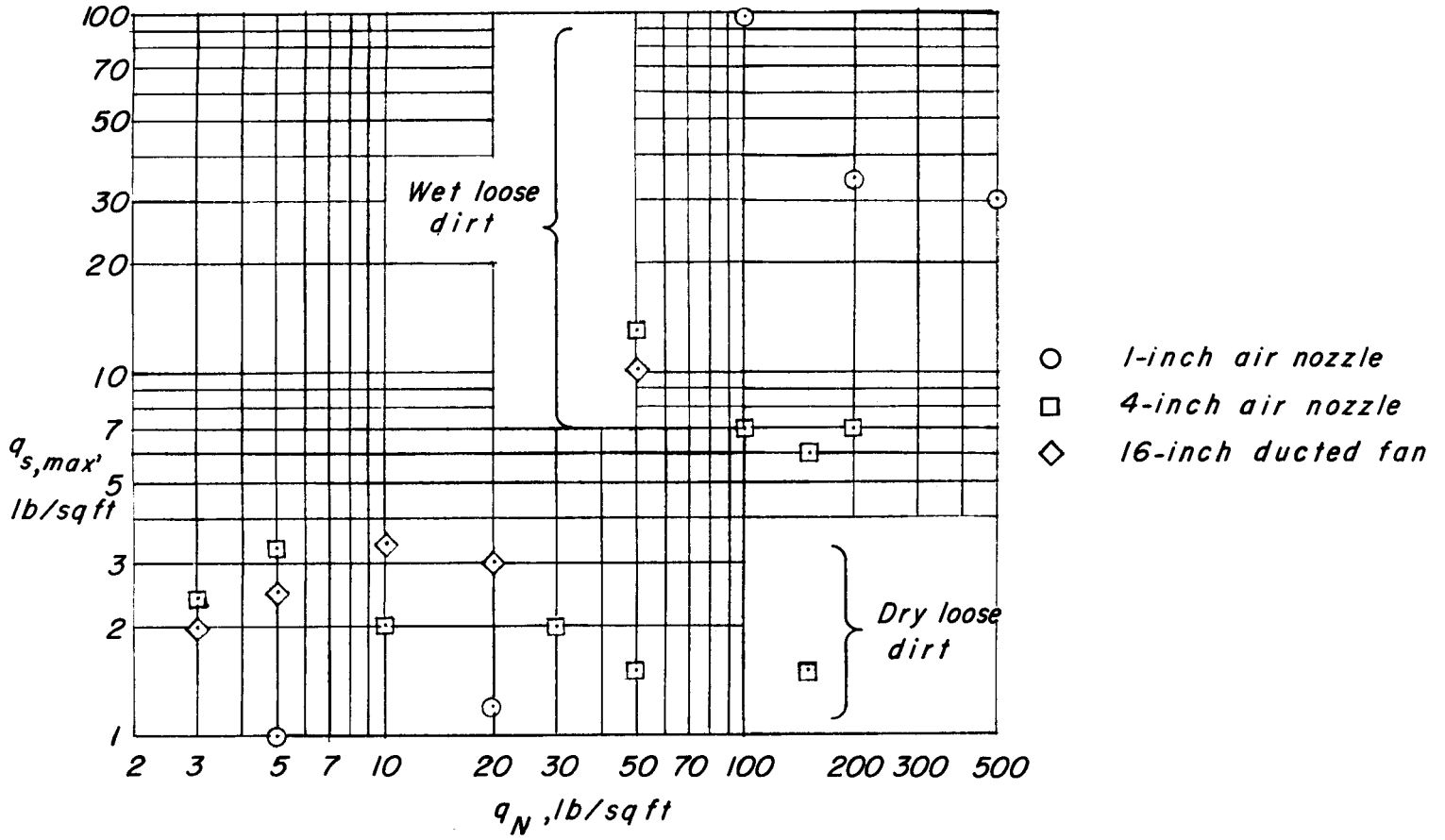
(c) Water.

Figure 8.- Concluded.



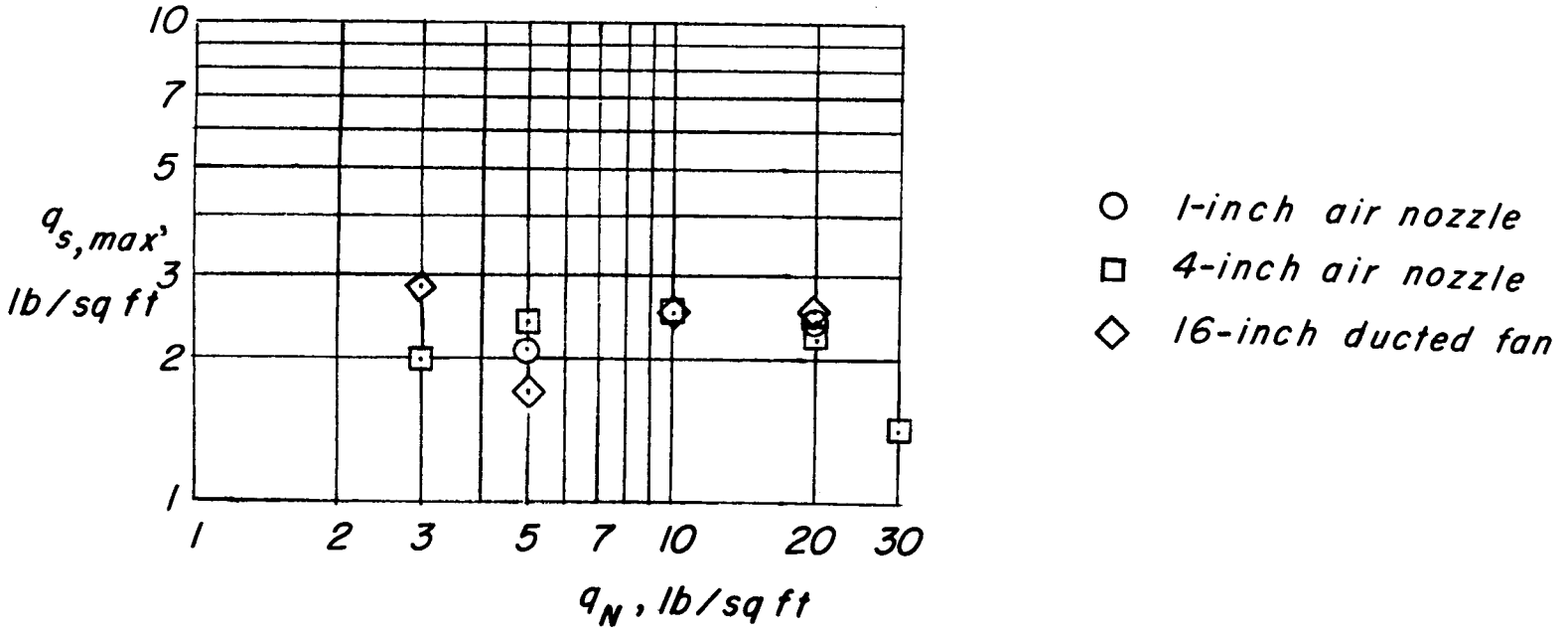
(a) Sand.

Figure 9.- Surface dynamic pressure at which disturbance started for various nozzle dynamic pressures.



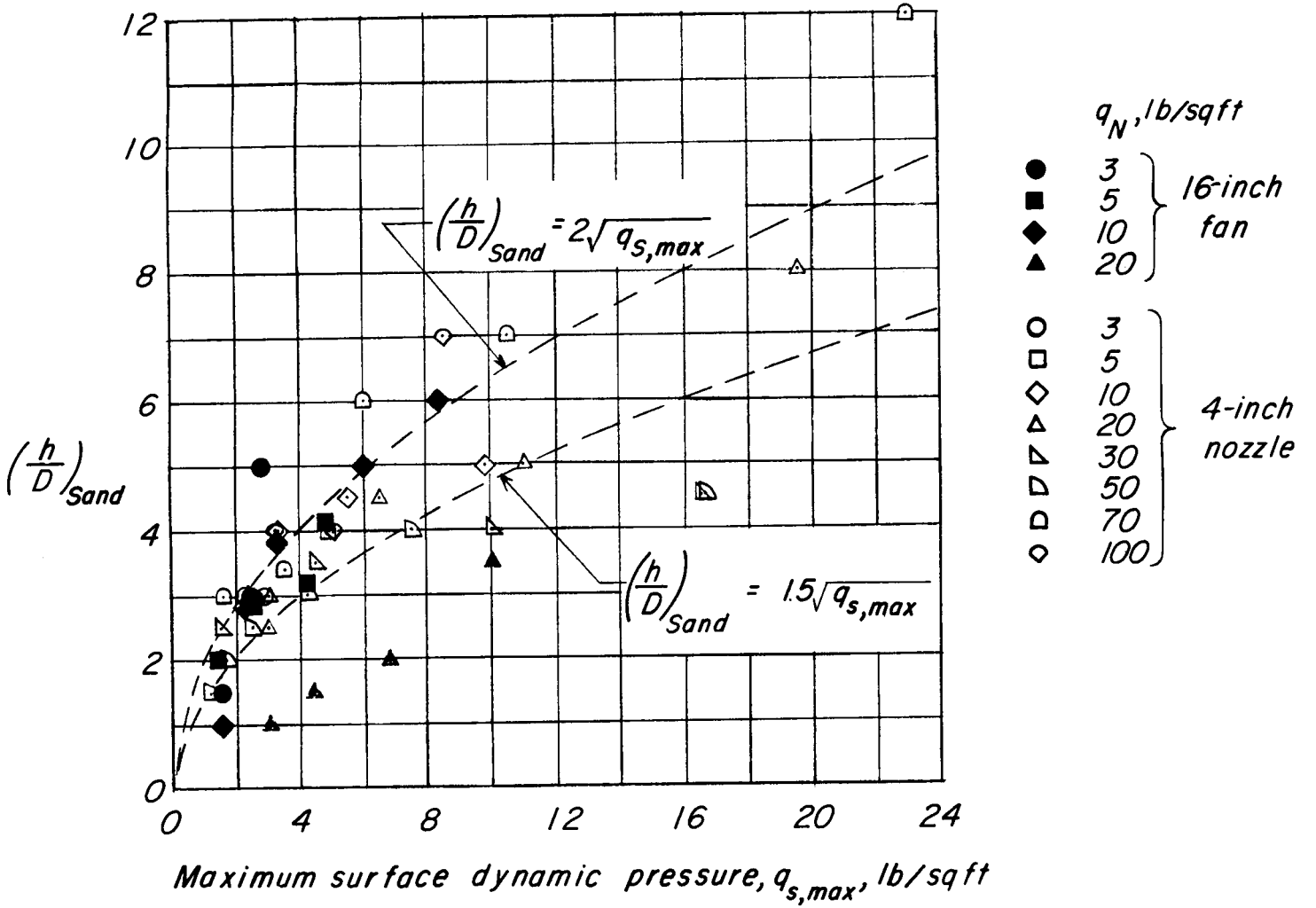
(b) Loose dirt.

Figure 9.- Continued.



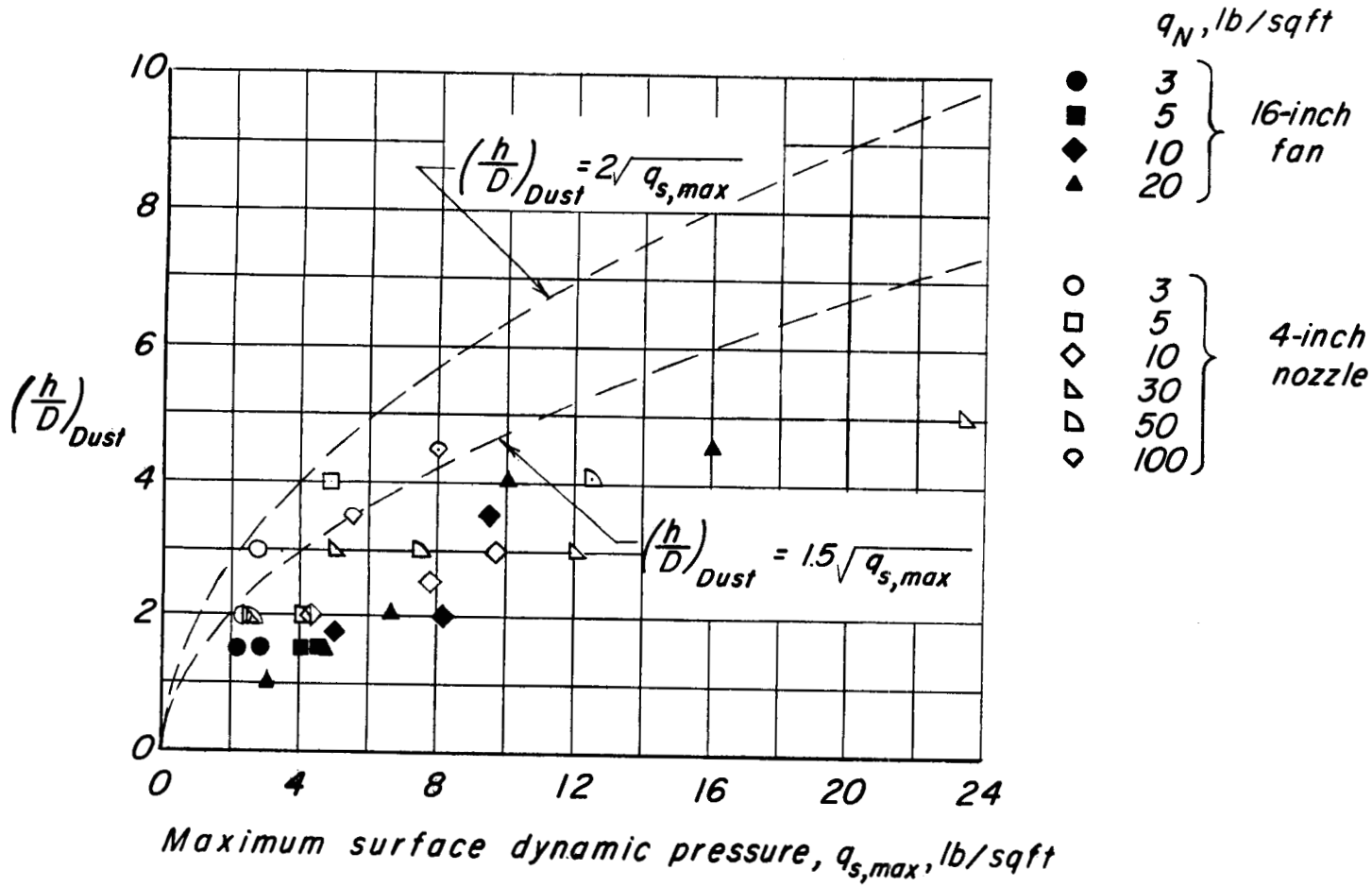
(c) Water.

Figure 9.- Concluded.



(a) Sand.

Figure 10.- Height at which sand and dust were observed for various surface dynamic pressures.



(b) Dust.

Figure 10.- Concluded.

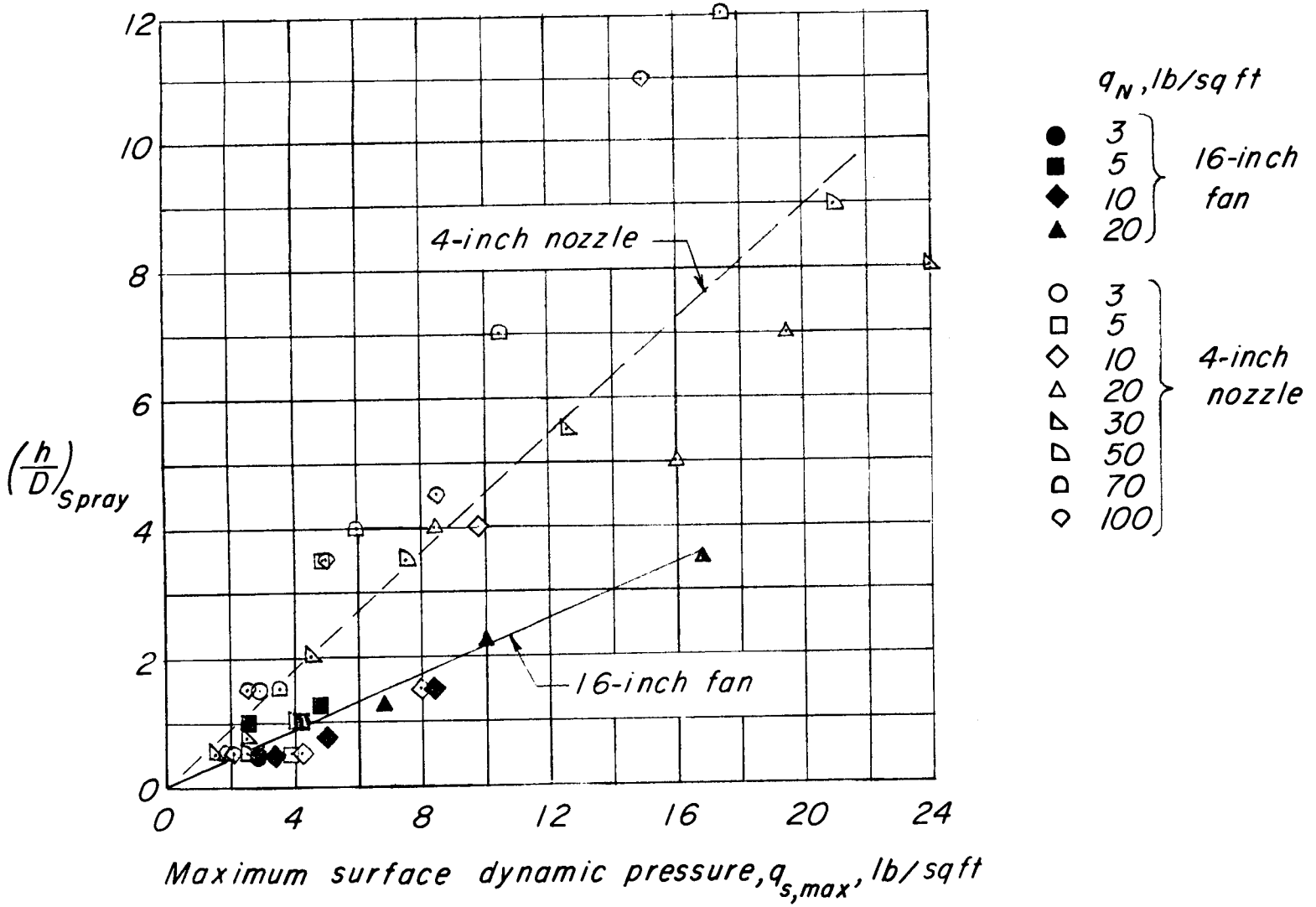
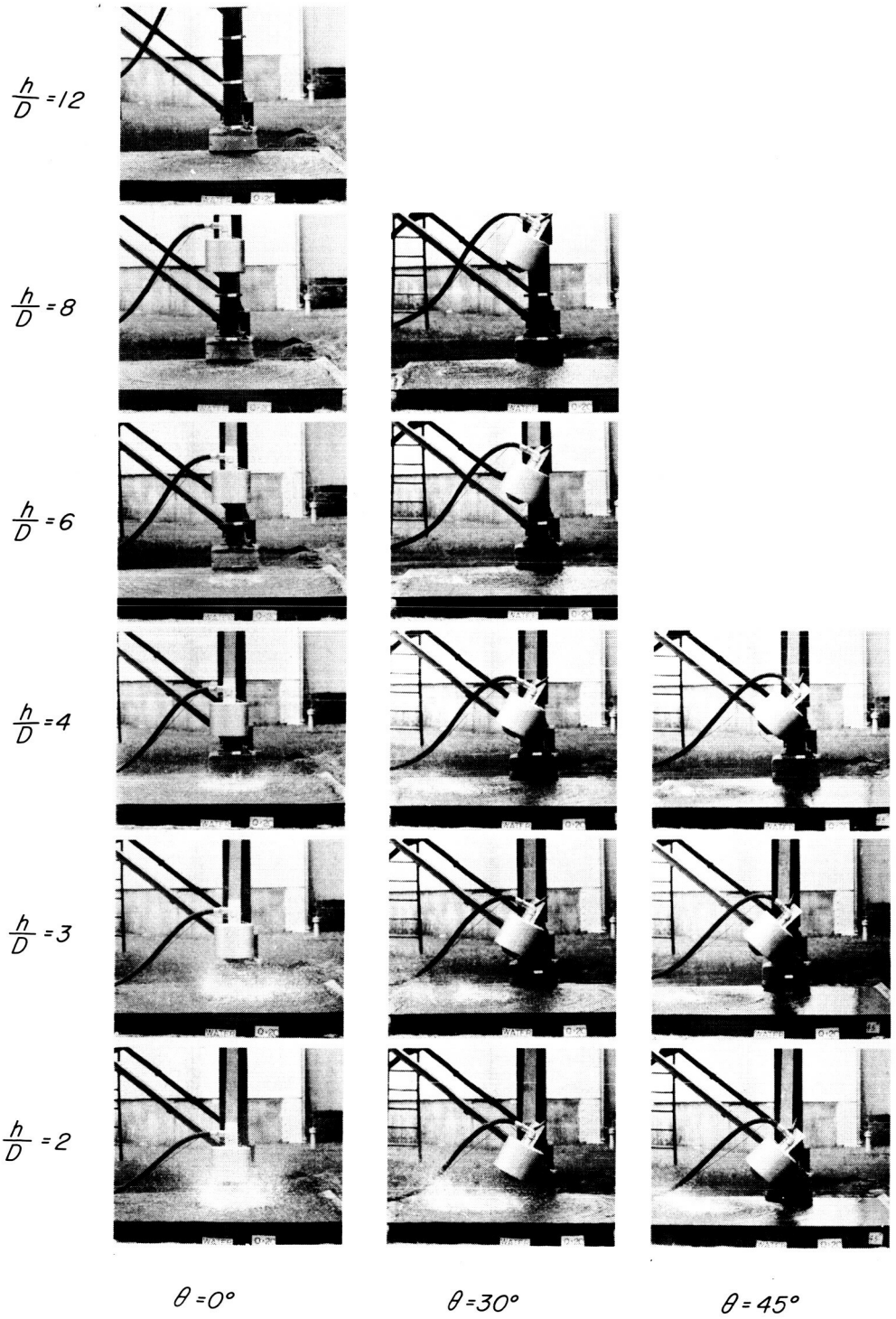


Figure 11.- Height at which spray was observed for various surface dynamic pressures.



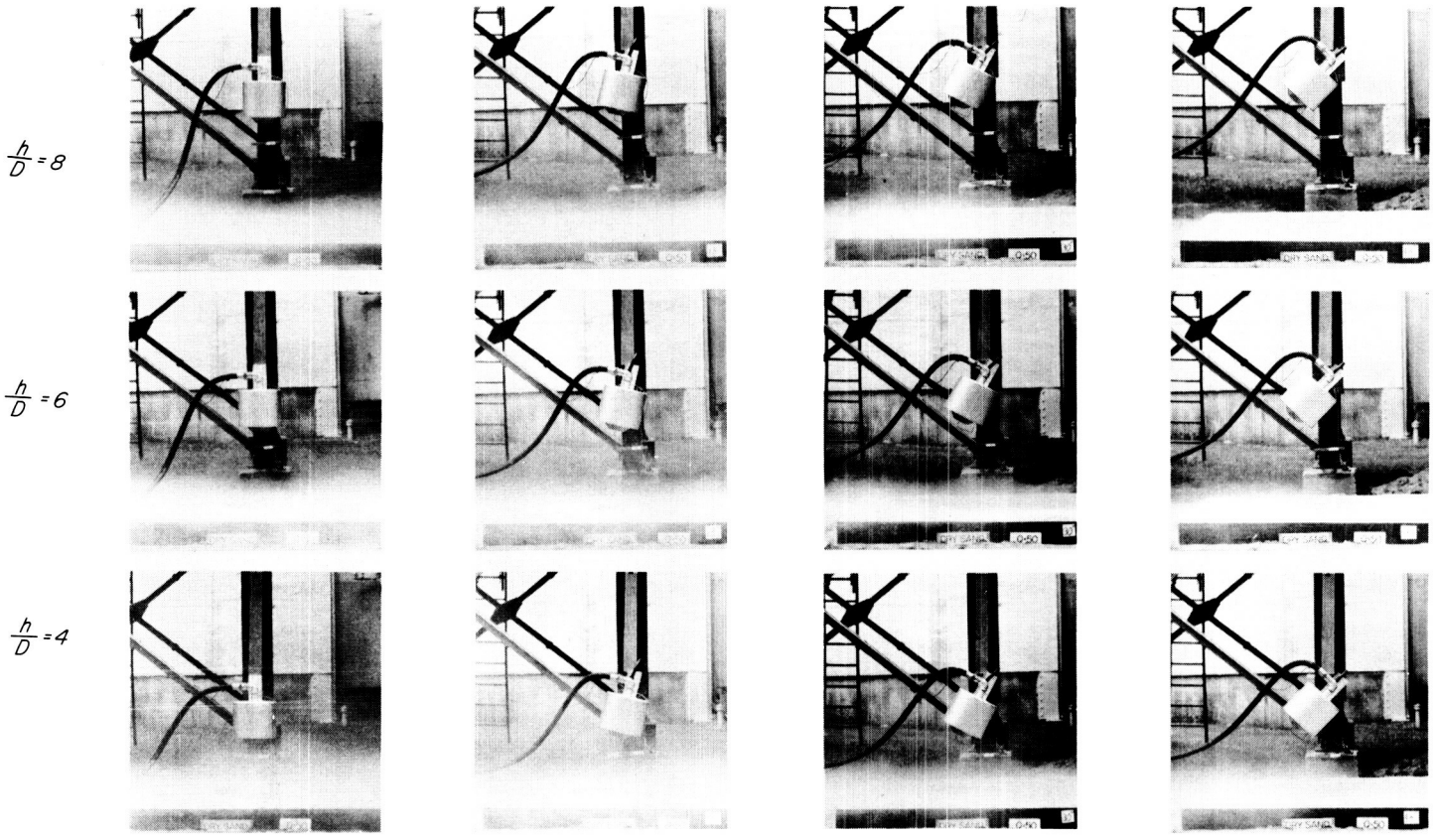
(a) Water; q_N = 20 lb/sq ft. L-59-1945

Figure 12.- Effect of inclining jet axis.

$\frac{h}{D} = 22$

$\frac{h}{D} = 18$

$\frac{h}{D} = 12$



(b) Sand; q_N = 50 lb/sq ft. L-59-1946